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Room 111, Headquarters
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From: U. S. Naval Forces, Germany, Office of the Senior U.S.Naval Liaison Officer, EUCOM HQ. Attn.: Technical Section (Medical) APO 403

To: Chief of the Bureau of Medicine and Surgery, Department of the Navy

Via: (1) Technical Officer, U.S.Naval Forces, Germany
(2) Chief of Naval Operations (Op-32-F2)

Subject: Marknagelung (Medullary Nailing) - Additional Translation - Forwarding of.

Reference: (a) Letter P3-5, Serial 243-Med, dated 22 April 1948 from Asst.Tech. Officer (Medical), U. S. Naval Forces, Germany.

Enclosure: (A) Translation of Book on Medullary Nailing by Prof. Dr. G. KUENTSCHER Project II, Folios VI - IX.

1. Because of its bulk Enclosure A will be forwarded under separate cover directly to each of the below listed recipients of this letter.

2. This is the final group of translations in this project which includes a wide variety of articles on the subject of medullary nailing, a method of treating fractures developed by the author of this work in 1940 and used extensively in Germany since that time.

3. This project was undertaken at first in 1946 by Commander Harry J. ALVIS, MC, USN., then Head of the Medical Section. The editing of these translations has been completed in the United States, he having been returned there in July 1948. The mechanical completion of this work has been continued by a portion of the Medical Section which is presently operating under the administrative supervision of the Senior U. S. Naval Liaison Office, EUCOM HDQTRS., U. S. Army, APO 403.

4. Attention is invited to the fact that this translation is from a manuscript prepared for the U.S.Navy Medical Corps and has not been published elsewhere.

5. The reserve supply of this work is limited. It will be forwarded to the Bureau of Medicine and Surgery, Publications Division on a Government Bill of Lading. Requests for additional copies should be directed to that office.

N. W. Abrahams
N. W. ABRAHAMS,
Captain, U.S.N.
Senior U. S. Naval Liaison Officer.

cc:
(see page 2).

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Project 2, Folio 6

THE MARROW NAILING METHOD

by

Professor Dr. Gerhard KUENTSCHER
Head of the Kreishilfskrankenhaus
Hesterberg, Schleswig-Holstein.

Translation prepared by:
U. S. Fleet, U.S. Naval Forces, Germany,
Technical Section (Medical).

[1949]

TABLE OF CONTENTS.

FOREWORD TO THE TRANSLATION.

Of all the developments of German medicine arising during the late war it is probable that no other attracted as much notice as the development of the Marknagel by Professor Dr. Gerhard KUENTSCHER. This procedure was first made known to English and American surgeons through the repatriation of prisoners of war who had been treated by this method. As it has been received by German surgeons when first announced, it was similarly observed with considerable skepticism by the English speaking surgeons. Immediately following the war's end this was one of the subjects looked into by medical investigators. Unfortunately there was not any considerable amount of clinical material available for examination and evaluation at any given point, attention was focussed on other problems, the war with Japan was still continuing and it is no exaggeration to say that the subject was skimmed over somewhat sketchily. Subsequently the subject fell into some disregard as being an untried innovation that still remained to be proven. The procedure was taken up by some surgeons and tried with indifferent success because they were beginning at a point which failed to take advantage of the experience already gained over the preceding six or seven years.

An investigation of the clinical experience with this procedure was one of the major interests which lead to the establishment of the Medical Section of the U. S. Naval Technical Unit, Europe in June 1946. Considerable field work had already been done before that time. It was felt that the greatest lack for English speaking surgeons was the inability to read and learn from the already published accounts - because they were printed in German and because they were available in only the most limited numbers. Accordingly the first item on the agenda when the Medical Section was founded was the translation of the book on technic which had been prepared by Richard MAATZ of the Kiel Clinic. A collection of reprints gathered from all over western Germany was studied and a representative collection selected for translation with the idea of demonstrating the experimental and basic background as well as the special considerations of hazards and complications along with the indications and contra-indications for the marrow nailing operation. This became Project II of the section.

In the pursuit of that goal a series of five Folios have already been distributed in a limited number. The fourth and fifth of these were the review by Prof. Dr. C. HÄBLER of his results in the use of the marrow nail. During all these years Dr. KUENTSCHER had contented himself with the publication in various journals of his experience. MAATZ, BOEHLER, HAEBLER and SOEUR have all published books on this subject. In the fall of 1946 after extended discussions and strong urging by the Head of the Medical Section, Dr. KUENTSCHER agreed to prepare his findings for the U. S. Navy Medical Corps so that they could be made available for the English speaking surgeons of the world. This task has been a long and arduous one for him. The

mere circumstances of maintaining oneself in post-war Germany are a full time occupation. In addition Dr. KUENTSCHER has conducted a busy practice under trying conditions in Schleswig, Schleswig-Holstein. Problems of supplies, of obtaining widely scattered X-rays for illustrations, of gathering together case histories have at times seemed almost insurmountable. Due to severe shortages of material many of the views were made on sensitized paper and although they served the purpose of the moment they were completely unsatisfactory for reproduction. Due to the severe bomb damage in Kiel and other cities many of the X-rays have been destroyed by fire or water or lie buried in the rubble. Some are lost forever, some could only be indicated by sketches but whenever feasible photographs were made. To avoid any additional delay the translation of the manuscript was undertaken piecemeal while it was still in preparation. This gave a rough preliminary translation which could not be completed until the illustrations were available for reference. X-rays could only be borrowed, photographed and returned. At this juncture the Head of the Medical Section was returned to the United States. The retyped rough translations have been transmitted to the U.S. for editing and returned for reproduction. So with Dr. KUENTSCHER struggling with the preparation of the manuscript in Schleswig in northern Germany, the illustrations being prepared in Heidelberg, the preliminary translation being made in Frankfurt am Main and the second editing being done in spare time from another full time occupation in Boston, Massachusetts and then returned to Heidelberg for reproduction, it is very clear that the much desired close collaboration between author, translator, illustrator and editor has been an impossibility. This has however, been only a mechanical separation for there has been no lack of determination, cooperation or earnest desire to bring this project to as early a successful conclusion as possible. That objective now seems in the near offing.

It is fitting that this large task should be concluded with this exhaustive work by the man who is the father of the entire idea. It is believed that the reader will find in this last group of the series of Folios the answer to almost any question he may wish to ask about the marrow nail. The particular virtue of this work and that of HAEBLER is that there has been no glossing over of failures, no reluctance to admit mistakes and no claims for the marrow nail as a cure-all for fractures. The orthopedist reading carefully this series of translations can begin years ahead of where he would begin without having read them for they contain the full experience and many observations based on thousands of cases.

For all the reasons mentioned before it is with a feeling of considerable satisfaction that this work is sent on its way. All those who have participated in its furtherance have felt keenly the fact that it could have been done better if we all could have sat down together to work on it. Throughout the entire organization involved in this task there has been the constant feeling that here was a contribution to man's welfare that would

relieve suffering and reduce financial loss to the peoples of the world if the word could be passed along. In its present form there has been no financial gain to a single person concerned in its preparation. This is a tribute to the author, Dr. Gerhard KUENTSCHER.

The limited number of copies of the translation in this form will be delivered to the Research Division of the Bureau of Medicine and Surgery of the U.S. Navy. Anyone interested in reading further in this series of translations should contact that office in Washington, D.C.

New Years Eve 1948

HARRY J. ALVIS,
Commander, Medical Corps,
U. S. Navy.

PREFACE

This book was written at the suggestion of Commander Alvis, MC, Medical Corps, U.S. Navy, and I am greatly indebted to him not only as to this suggestion but also to his very energetic help in connection with the writing of the manuscript and its translation into the English language.

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This book was written particularly for American readers. The progressive attitude of the people of the U. S. which characterizes U.S. science and research work and to which the U.S. owes her leadership in the world has from the very beginning and at all times been alert to make use of technical innovations. In contrast to the conditions in Europe, the operative treatment of bone fractures is very common in the U.S. The technique of the marrow nail operation, to which this book is exclusively dedicated, demonstrates a special development of the operative technique of the treatment of bone fractures and therefore this book should find a hearty welcome by U. S. surgeons and orthopedic surgeons because it will serve their interests.

At the same time, however, this publication will be of greatest interest also for the patient, who, particularly in the U.S., is interested in leaving the hospital as soon as possible. By applying the principles described in this book this understandable desire of the patient will be served.

The marrow nail operation was invented and elaborated by myself in 1939, at a time when the war had already broken out. This may explain the slow spread of information concerned with this method in foreign countries. During the war it was mainly practiced in Austria, somewhat later in Sweden, Finland, Russia, England, Holland, Belgium, Switzerland and in Spain. In Germany, where this new method was disapproved in the beginning after it had been announced at the Surgical Congress in Berlin in early 1940, the new method spread widely, sometimes in a rather precipitate manner. The publication of a series of excellent books about this subject can be ascribed to this fact. We refer to the excellent publication by BOEHLER (Vienna), which already in 1945 was in its 11th edition, and the publications by HAEBLER (Hannover). A new, more detailed edition of this book will be published shortly. Furthermore I must mention the publications by SAEGESSER (Bern) in his manual of surgery, and the book about the marrow nail operation by SOEUR (Brussels). During the war the author of this book was not in a position to write a book of his own about this subject, and the publication by KUENTSCHER and MAATZ mentions only his name. In reality that book was exclusively written by MAATZ. Besides this such a great number of publications appeared in newspapers, so many dissertations have been written and speeches made at Surgical Congresses that this author found it impossible to read all those publications because of the conditions prevailing in Germany during and after the war. Due to

these circumstances some useful contribution to this project may not have been evaluated at its true merit in this writing, and I therefore have to apologize for that.

The treatment of bone fractures and particularly the marrow nailing operation require special skill, and therefore special consideration has been given to the description of the technique. I had to do that in order to help avoid errors, setbacks, and disappointments to all those who are not acquainted with this method. I had to undergo these experiences myself. From the very beginning, however, I must say that the practice of this method should be reserved only to those surgeons who are well acquainted with bone surgery and septic surgery besides. Mastery of the technique of these fields is unconditionally presupposed.

The above mentioned publications deal exclusively with the technique to be applied and this writing can only be a supplement to them. Besides this, however, the entire field of the marrow nail operation and its scientific evaluation will be dealt with and it is my opinion that this circumstance justifies the publication of this book. I would like to thank not only my collaborators but all those authors who have contributed to improving this method. I have to be especially thankful to Mr. E. POHL (Kiel) who has constructed the instruments necessary for this kind of operation. His inventive prowess and energy made it possible to overcome most of the technical difficulties.

Schleswig, February 1947

G. KUENTSCHER

Resume of the Monograph "The Marrow Nailing".

In Chapter I the disadvantages and dangers of the hitherto known methods for the treatment of fractures are discussed. It is próved by some statistics that most of the disadvantageous effects after such treatment are due to the methods applied. This is particularly true as regards the prolonged immobilization of the limb. In order to obtain better results in the healing of fractures modern surgery particularly tries to counteract the harmful after-effects of the fixation. On the other hand, however, theoretical research work and practical experience as well have proved that a long lasting and stable immobilization of the fracture is absolutely indispensable for the bony bridging over of the fracture cleft. Otherwise we must fear the development of a pseudarthrosis due to the failure of any bony healing to appear. Consequently the disadvantageous effects of such an immobilization with its serious damaging effects upon the musculature and joints must be taken into consideration. The art of treating fractures consists in finding a compromise between the immobilization of the fracture and the early subjecting of the limb to exercises to counteract the disadvantageous effects of the immobilization. The new method of marrow nailing, however, is no compromise but an amazing new solution of this problem. The demand for fixation is fulfilled to 100 % and at the same time the desire for early motion of the injured limb is fulfilled in a way such as cannot be obtained, not even partially, by any other method.

In Chapter II it is shown how effects of this kind can be obtained and how the fragments become strongly united immediately by means of a stainless steel nail which is inserted into the marrow cavity. Wabbling movements are no longer possible and the painfulness subsides immediately. Soon after the operation the limb may be subjected to exercises because the splint is no longer required. The patient may get up early, and in this way the psychic and physiological disadvantages of long confinement to bed are eliminated. At the same time the local blood circulation becomes better, muscle atrophy and stiffening of the joints are avoided. By means of some statistics it is proven that in practice a considerable percentage of fractures may be treated according to this new method. At the same time the economic advantages are demonstrated. The period of treatment and hospitalization and the missed working days can be considerably decreased. The other results obtained in this way as to restoration, shape and mobility of the limbs are demonstrated by the findings at late examination. Furthermore it is shown that in cases treated in this way the much feared edema of the leg does not develop.

Chapter III is concerned with the biological and physiological principles of marrow nailing. In the beginning the function and construction of the bone is dealt with, and at the same time its reaction as to weight-bearing and strain is described. In case of an excessive strain, tension peaks occur at those spots at which harmful forces develop and at the same time we see

mechanically provoked bone and joint diseases. It is shown that first of all during the healing of fractures, damage occurs at those spots where harmful tensions develop, and that in this way the development of a pseudarthrosis can be explained. It is shown that those harmful forces are kept away from the fracture cleft by means of the marrow nail. Furthermore, for the first time it is possible to exclude even the slightest wabbling movements. Thus from the biological point of view the marrow nailing must be considered to be the most favorable method.

In the second part of Chapter III the physico-chemical processes developing in the fracture cleft are described in detail and at the same time the reasons for the development of callus and the healing process. It is shown that even in those cases in which the entire marrow was destroyed and the marrow cavity was filled with metal a healing of the fracture is obtained and that by the chemical irritation of special marrow nails a formation of callus can be obtained even without a fracture.

In Chapter IV the dangers connected with the new method are considered. The results obtained in animal tests have been confirmed by the results of thousands of nailings in humans. No noteworthy impediment of the formation of callus can be demonstrated, and at the same time general damages to the organism are not to be feared. This later is proved by statistics concerning the blood pictures. Then the local damages to the bone by the metal of the nail are described, furthermore the processes developing during the fracture, the breaking of the nail and the wandering of the marrow nail. In a series of examples and statistics the dangers of embolism and shock are dealt with in detail and at the same time the measures taken against them are mentioned. It is proved by statistics that the danger of an embolus is not greater than with other methods. Finally, reference is made to the danger of infection in marrow nailings. It is proved that that danger is considerably less than in the operative treatment of the fracture, because the marrow nail is inserted into the marrow cavity through a small stab incision which is located at some distance from the fracture site. The symptoms and the course of the bone infection in marrow nailings is described and several examples are given. The ring sequestrum is the typical sequestrum of faulty marrow nailing.

In Chapter V the technique of marrow nailing in simple fractures is described in all details and numerous examples are referred to. Then we deal with the indications for an operation of this kind. It is shown why closed nailings in children should be made only exceptionally despite the fact that statistics concerning nailings in children prove that such an operation has no particular harmful effect upon children even in those cases in which the nail penetrates the line of growth. The most essential advantages of the nailing are of no importance in children. Then we deal with the suitability of fractures for marrow nailing and come to the conclusion that every fracture is suitable for marrow nailing in which an absolutely stabile union of the fragments can

be obtained with the marrow nail. The stability of such a union depends on the location of the fracture, on its shape and finally on the anatomical conditions. The armamentarium necessary for the nailing operation is dealt with in detail and at the same time all those instruments necessary for reduction which are referred to in literature. Finally we have to deal with auxiliary means for reduction. In another part of this chapter X-ray apparatuses are described in detail and by means of detailed statistics it is shown that the dangers developing from this aspect are considerable not only for the patient but also for the surgeon, and that those dangers can be eliminated by simple auxiliary means. Despite the good statistics regarding infection a particularly strict asepsis is required for this operation and is described in detail. Finally we deal with the selection of the appropriate anaesthesia and the correct selection of the length and thickness of the nail.

In the second part of this chapter special consideration is given to the nailing of the femur, the subtrochanteric and portrochanteric fracture, the fracture of the forearm and the arm above the elbow, the fracture of the collum chirurgicum, the clavicle, and fracture of the finger. For all these cases the shape of the marrow cavity is described in detail as well as the appropriate position of the patient during the operation, the shape of the nail, its insertion, and finally the further course with the mistakes and dangers to be encountered in each of the different operations. Reference is made to numerous examples. After that the removal of the nail is described, furthermore the instruments for the extraction, the method for locating the nail head and finally the extraction of the nail itself, the sawing through of the nail, the removal of broken nails, and finally all possible mistakes and dangers developing during these different operations.

Chapter VI is concerned with the application of the method beyond the treatment of the bone itself. Many advantages of the new method have proved their value in a large number of cases, first of all the absolutely stabile union of the fragments and the possibility of subjecting the limb to early exercises and weight bearing. Apart from this it is shown that the nail does not simply replace the screws, wires, etc. which were used in the previously known methods. On the contrary we have to deal here with an entirely new biological method of operation and that is: preservation of the periosteum as far as possible because the nourishment of the bone depends largely on it. In this way quite different healing results are obtained and the danger of infection has decreased. This is due to the fact that poor blood circulation in a bone hampers its defense forces against infection. But also in those cases in which an infection has already occurred, the respective consequences will not be so serious because sequestrum formation is not observed. With this new method the operative incision is kept as small as possible, which is of greatest importance also from the physico-chemical point of view. Any operation causes an acidification of the tissue which

is the stronger, the larger the operation. That acidification may be so strong that the conditions developing in this way may be compared with those in a secondary healing. After that we deal with the indications for osteotomy and the method to be used in case of a nailing. Then the different marrow nail osteotomies are referred to in detail as well as the technique to be applied, their dangers and the mistakes which are often made in this connection. Numerous examples are given for that. We deal with the marrow nailing of 1) fractures with the fragments in bad position, 2) fractures which have healed in bad position, and 3) fractures with delayed healing or which have not healed at all (pseudarthrosis). Then it is shown how to shorten and lengthen limbs. Only in the lower extremities should lengthenings be made whereas the upper extremities should in general be shortened. For the first time it is possible to obtain lengthening in a secure and simple manner by using marrow nails. A shortening of the limb should be made in case of gunshot wounds, and also in those cases where due to defects of vessels and nerves a lengthening of the damaged leg cannot be performed. For the first time it is possible to obtain a secure and accurate shortening of the two forearm bones as proposed by HENLE for cases of ischemic contractions. According to the theoretical considerations referred to in chapter III marrow nailing is the method of choice for the treatment of pseudarthrosis. In pseudarthrosis of the lower extremities the simple marrow nailing will suffice whereas in the upper extremities additional methods must be applied which are described in detail in connection with the forearm and the arm above the elbow. Many examples are cited to demonstrate the advantages and disadvantages of these methods. Then we deal with the marrow nailing operation in case of deformities of the bones; in the first place in connection with the subtrochanteric osteotomy. Then reference is made to different methods according to whether we have to deal with an adduction, flexion, or abduction. At the same time PAUWE's subtrochanteric osteotomy with the marrow nail is demonstrated. Then we deal with the marrow nail osteotomy in case of bandy legs and knock knees, with the supracondylar osteotomy and the use of the nail in foot deformities. After that non-malignant and malignant tumors are described in connection with the nailing. In such a case the nail is able to restore the stability of the bone for the lifetime of the patient. In this way pelvic casts are no longer required and irradiation is very much facilitated. Finally we deal with the prophylactic marrow nailing in the imperfect osteogenesis and many examples are given for that. At the end of this chapter detailed statistics of the successes obtained with the osteotomy are given and the results obtained with the marrow nailing method are compared with other methods.

Chapter VII is concerned with the marrow nailing of compound fractures, fresh gunshot fractures, and infected fractures. In general the healing results obtained with compound fractures are much more unfavorable because of the very frequently observed secondary healing which is due to the marked acidification of the tissue.

Serious injury to the musculature, joints, nerves, and vessels are observed. After that we deal with the results obtained in dog tests and then the application of the method to humans. Statistics prove that also in this field the marrow nail method can compete with the previously known methods. In the following chapter we show the application of the new method in fresh fractures and HEIM's, BOEHLER's, and this author's methods are described in detail. Many statistical references are made and many examples are given. Finally we have to deal with the nailing of already infected fractures. Here, in this field, the advantage of the absolute immobilization of the fracture cleft with the elimination of all waddling movements is fully realized. Then we deal with the use of the marrow nailing in septic infected fractures, in suppurating fractures, and fistulating pseudarthrosis during the quiescent phase in which elevated temperatures are not observed and the blood sedimentation rate is normal. Here extremely favorable results are obtained despite the fact that so far Penicillin has not been available. The end of the chapter is concerned with the use of Penicillin and Supronal in marrow nailings.

Chapter VIII is concerned with the use of the method in connection with the fixation of joints. Also here the marrow nailing shows good results which is due to the fact that with the insertion of the nail the joint becomes stiff and at that very moment it is no longer painful. Also this operation can be made in such a way that the joint need not be opened. A stab incision distant from the joint is made. The incision is small and consequently even weak patients can be subjected to such an operation. Furthermore we have the advantage that external splints are no longer required. In many cases however this closed nailing does not suffice to obtain a bony bridging over of the joint. Thus in a second operation which is made later the joint must be destroyed by means of KIRSCHNER's splitting etc. Also here the operation is small. The following part of this chapter is concerned with the open and closed marrow nail arthrodesis of the joint. By the use of an angulated nail the knee joint is fixed in a slightly flexed position. The indications are dealt with in detail and some examples are given for the closed and open nailing. Also in case of an open nailing, as for instance because of a knee resection due to tuberculosis, the new method shows great advantages. In much the same way we deal with the arthrodesis of the shoulder, elbow, and ankle-joint. In many cases it will be possible to eliminate incomplete flat-foot and splay-foot positions.

Chapter IX is concerned with the marrow nail arthroplasty. In this field the nail has a double function. In connection with the formation of a new joint the nail has not only to be a gliding plane but at the same time it must be the guiding mechanism for the joint movement. We do not however dispose of much experience in this special field so that this chapter is of only theoretical significance for the time being. Great hope however has to be attached to this special field for the future. After a description of our animal tests we deal with the arthroplasty of the hip and elbow joint and finger joints and some examples are given for that.

Chapter X is concerned with the attitude of the patient and the surgeon towards this new method.

CHAPTER I

Introduction

The oldest field of medicine is the treatment of accidental wounds. Here, in this special field, the cause and the effect of the disease are readily recognizable and are not hidden behind some other condition, as is for instance liver or kidney diseases. Concerning these latter diseases, medical science recognized only very late the proper cause of the processes, and divine and other causes, or even diabolism were blamed for their development. Attempts made to help the patient by praying, by sacrifices, or even by witchcraft. In case of an accident, however, it is more obvious to look for a "causal treatment" and it is a matter of fact that, even considering the primitive means which were available, such a treatment was quite possible. So in the ages past there must have existed the beginning of emergency medicine and in antiquity and in primitive nations a highly developed emergency medicine is readily traceable. The science of surgery had gained recognition with other fields of medicine only lately and it has received its greatest emphasis only in modern times with the knowledge of antisepsis, asepsis, and anaesthesia which have rendered all parts of the human body accessible to treatment. For many types of diseases the surgical treatment is the method of choice and at present surgery is at its peak. The fields dominated by modern surgery will in the future become less important again and principally those now in the foreground will be limited considerably. These days the main activities of the surgeon are: The treatment of the malignant tumors of the stomach and intestinal tract, of the chest, brain, of the extremities, and the cure of inflammatory processes in the appendix, of the peritoneum, gall bladder, stomach (ulcer), pleura, tendon sheaths, of the perspiration glands, etc. In most of the cases the surgical treatment is not absolutely causal. So for instance by treating the cancer of the rectum the agent of the cancer which is still unknown cannot be approached but the entire rectum must be removed and the abscess opened. Sulfonamides and Penicillin are modern means at our disposal to approach certain bacteria directly and we can take it for granted that all these means will be still further developed in the future. After that the panaritium will no longer be incised, but we shall administer bactericidal drugs and one day, let us hope, mankind will have available a "drug" against malignant tumors. Then surgery will look quite different, for the entire field of so-called "major surgery" will no longer exist. We, the surgeons shall not complain about that. Tumor surgery and the serious mutilations inflicted by it are ugly: The excision of the entire larynx, the excision of the breast with the "cleaning out" of the armpit, the amputation of the rectum with the application of an artificial anus on the abdomen, the exarticulation of the hip with the removal of the pelvic bone. All the ingeniously invented and wonderfully developed operative methods will be applied much less frequently in the future.

Similar to the conditions prevailing today, the situation once was the same concerning the removal of the tuberculous lymph nodes of the throat. The situation will not differ so much with regard to the operative treatment of hernia, of congenital malformations of the body etc. The main task of all surgery will be the science of first aid practice, i.e. that field from which surgery originated. The oldest field of medicine will one day be the great future.

These days, however, surgeons are obliged to deal much more intensively with the practice of first aid because of the war with its enormous number of injuries, a great many of which still exist today. In this special field - as in all the others - the surgeon is confronted with problems which very often are as difficult as those caused by the treatment of tumors. An osteotomy may be much more complicated than the resection of a tumor of the colon or of the pancreas. Therefore the prospective development of surgery will require much more of the surgeon regarding his capacities as a medical doctor, artist, and scientist. All possible progress in this field is worth mentioning and this book is dedicated to this purpose.

In the foreground of first aid stands the treatment of bone fracture because of the seriousness of its clinical picture and its consequences and because of its difficult treatment.

Each treatment of fracture must on principle consist of keeping the fragments in good position for whatever period of time is necessary to enable the body to bridge over the fracture cleft by bone. The oldest method for that purpose is to apply an external splint which in general extends beyond both joints adjacent to the fracture site. The unpadded cast of BOEHLER is most suitable because it best fits the injured limb and therefore it represents the most certain means of keeping the fragments in good position.

Great dangers are, however, connected with the fixation: An atrophy of inactivity of the musculature may occur which must be ascribed to the immobilization of the limb. The stiffening of the joints depends on the age of the patient and on the duration of the fixation. BOEHLER asserts that in simple fractures a plaster cast applied in the correct way prevents a stiffening of the joints and according to the results of animal tests made by LOEWENSTEIN even a long lasting fixation will not result in a stiffening of the joints. Therefore, it must be concluded that other causes must be taken into consideration. It is my opinion that the acidity which develops in the tissue due to the mechanical inflammation caused by the fracture is of utmost importance. This acidity is stronger in those cases of a connective tissue proliferation after operative trauma or even with infection in cases of secondary healing. (See Chapter III).

It is a matter of fact however, that in practice, even in simple fractures, considerable stiffenings may occur after treatment with a plaster cast. The tendons adhere to their sheaths.

Even the blood circulation of the fixed extremity is considerably involved. We know how important the musculature is for the return transport of the blood into the veins. The constant change of the contents of the skin vessels no longer exists because the innumerable minor stimuli of the skin caused by changes of temperature, movements, touching and change of pressure in the cast are nearly completely blocked off. The consequence of all this is the edema which, despite appropriate treatment, often lasts many years.

Not only the injured extremity but also the entire organism shows impairments which must be ascribed to the fixation. Particularly in case of fractures of the lower extremities the strictest confinement to bed - in most of the cases even in a supine position - is required. This means a damaging effect upon the general blood circulation with which is associated the danger of the development of pneumonia, thrombosis, embolus, etc. At the same time there exists the danger of decubitus and necrosis due to arterial compression, and this is also due to the fixation. Also in these cases old persons are much more endangered than young people and, last but not least, we must not forget the psychic state caused by prolonged confinement to bed.

Statistics prove how great these dangers are, and I would like to refer to some statistics published by BOEHLER:

According to the report of the Ministry of Interior, Vienna, the following number of persons were awarded permanent pensions from the "Workman's Insurance Companies against Accidents" in Vienna and Lower Austria:

Femur fractures:	89.2%	had	perm.disab.	of	42.17%	on	an	average
Leg fractures	80.7%	"	"	"	" 27.39%	"	"	"
Upper arm fractures	78.1%	"	"	"	" 23.50%	"	"	"
Forearm fractures	62.0%	"	"	"	" 13.08%	"	"	"

These statistics include all the accidents between 1907 and 1911 which were insured by the Workman's Insurance Company against Accidents.

In 1914, THIEM, who is a well qualified expert, has published a summary of his investigations which includes the following insurance companies: Fund for the Benefit of Poor Miners, Industrial Trade-Union, and Agricultural Laborers:

of 428 femur fractures	289 = 67.5%	received	contin.	disab.	awards
" 2443 leg fractures	983 = 40%	"	"	"	"
" 369 fractures of both forearm bones	143 = 39%	"	"	"	"

In 1929 IUETZ published a summary of the results made in 100 fractures by the German timber trade union. He observed that

of 47 thigh fractures	47=100%	received	contin.	disab.	awards
" 86 leg fractures	82= 96%	"	"	"	"
" 37 upper arm fractures	36= 97%	"	"	"	"
" 41 forearm fractures	37= 80%	"	"	"	"

In all these damages it must be taken into consideration that the greater part of them are not due to the accident but to the treatment, i.e. to the fixation. In most of the cases pensions are not paid because of a bad position of the fragments but because of stiffening of the joints, muscle atrophy, etc.

Damages of that kind are treated by the so-called after-treatment (physical therapy, exercises, massage), which in many cases lasts much longer than the treatment of the fracture itself. (Compare figures published in Chapter II). Therefore the after-treatment is very expensive. It requires much experience and skill and in many cases it is more painful than the care of the fracture itself. Nevertheless in many cases it will not result in a complete restoration because many of the above mentioned damages are irreparable.

The aim of modern therapy is to keep damages by fixation at a minimum by fixing as few joints as possible and by subjecting the injured limb to exercises as early as possible. This is the important second principle in modern fracture therapy. It is contrary to the first principle which requires the stabile immobilization of the limb. The complete fulfillment of the first principle excludes the fulfillment of the second principle. In order to achieve an undisturbed healing of the fracture the immobilization of the limb must be as exact as possible as will be described in detail in chapter III. For the same reason immobilization must be maintained until a final healing is achieved as BOEHLER has pointed out in his publications. This means in cases of thigh fractures an immobilization of at least 9-10 weeks.

The above mentioned first principle is indispensable for the healing of the bone. The second principle, however, must be met in order to prevent a damaging effect upon the muscles, joints, and vessels.

The art of treating fractures consists in finding a compromise between the two contrary principles. So we see some moderation as to the fixation of radius fractures. The dorsal plaster splint is attached in such a way that the finger and elbow joints are freely movable. The fixation is not absolute of course because the plaster cast does not fix the bone and the soft parts are between the bone and the cast. A couple of days later the cast does not fit snugly due to the resorption of edema and hematoma. Furthermore the fixation is not permanent because the fixing cast must be changed several times during the treatment. Fixation and movement are united in BOEHLER's plaster jacket for the treatment

of fractures of the spine. A considerable decrease of the principle of fixation is noticeable in the traction method in which mistakes are frequently observed in connection with the first mentioned principle. On the other hand in the operative treatment of bone fractures this principle is often too much considered. Here the fixation is achieved not only by means of screws, plates, wires, etc., but an additional plaster cast must be applied because the above mentioned means alone do not suffice to keep the fragments in place. In this method other damages are to be observed in addition and at the same time the danger of infection exists. The hematoma which is so important in connection with the healing of the fracture is removed. The periosteum is separated more or less from its nourishing vessels and the connection between the bone and the periosteum is separated, etc. In this connection the periosteum is most important for the formation of callus (Chapter IV).

A good compromise is the nailing of the neck of femur. The union achieved by the nail which consists of three lamella (according to the principles of Smith-Petersen) is stabile enough. It is not immovable because the nail is lying in the spongy bone tissue. Weight bearing however is possible 6-8 weeks later. (Some authors have however no objections to subjecting the injured limb to weight bearing after a lapse of 2 weeks). Through the completion of the method by JERUSALEM and IVEN-JOHANNSON the nailing of the neck of the femur is not handicapped by the mentioned serious disadvantages of the operative treatment because the nailing operation is made "extra-articularly", i.e. without opening the fracture.

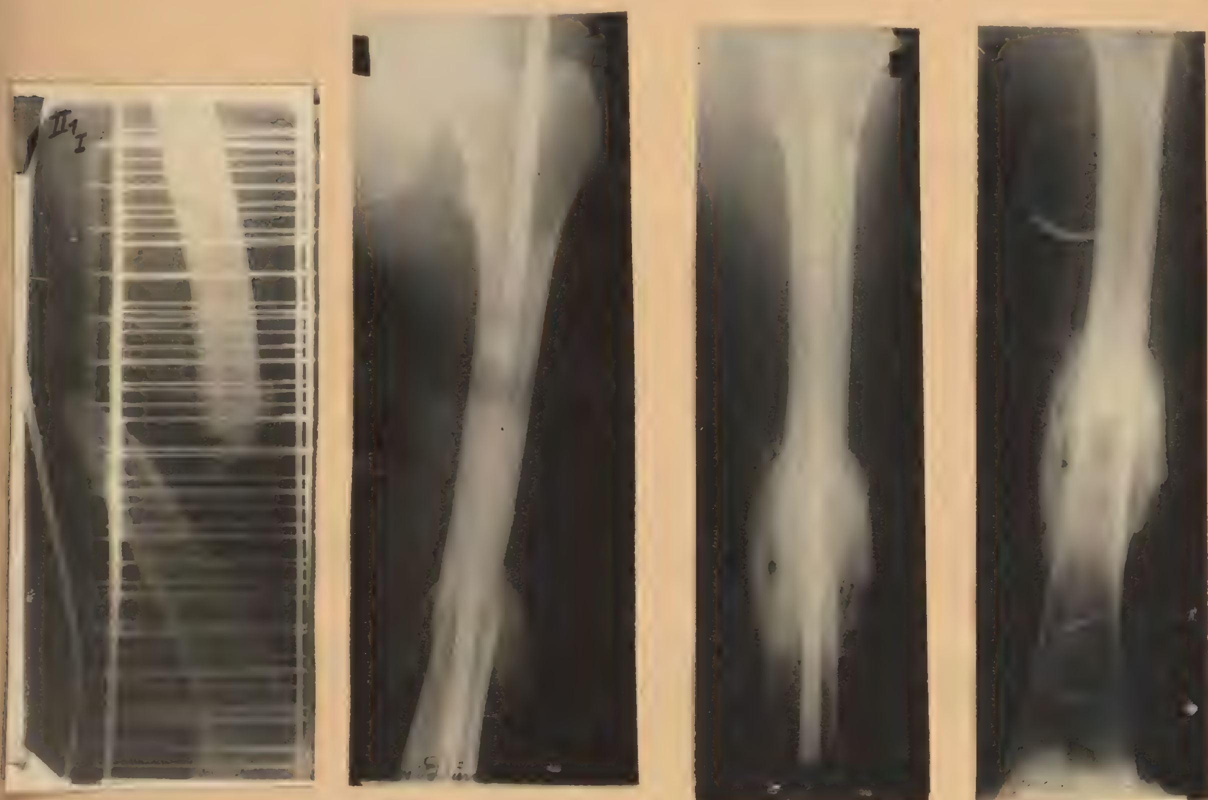
The new method of marrow nailing must be considered as an ideal solution of the problem in question. The "ideal" marrow nail operation is no compromise but a 100 % fulfillment of both principles.

CHAPTER II

General Data about the Marrow Nailing

The principle of the marrow nailing operation consists in the use of a stab incision some distance from the fracture cleft and the insertion of a steel nail - the marrow-nail - into the marrow cavity of the broken bone. The stab incision is sutured over the nail. In this way the two major principles of modern treatment of fractures are fulfilled at one time despite the fact that they are contrary to each other. This fulfillment is so complete that no other method offers similar success.

By using steel, the union of the fragments is so stabile that the fixation alone suffices to resist the strong forces of the musculature and the dynamic forces acting when the injured limb is used. Therefore an additional plaster cast is not required. The fracture is "plated" from within and therefore a true "stabile osteosynthesis" is obtained.



a b c d

Illustration 1. Example of the marrow nailing of a thigh fracture

a) before the marrow nailing
b) immediately after the nailing
c) shortly before the extraction of the nail
d) after the extraction of the nail

In this way the principle of an "uninterrupted immobilization" as long as possible is fulfilled 100% because the marrow nail is kept in the bone until healing is achieved.

The union is so strong that the limb may be subjected to exercises immediately i.e. as soon as possible and restrictions must not be made in this connection. Thus the second principle is fulfilled and in such a way as has at no time previously been considered possible. So, for instance, a patient who suffered a thigh fracture was able to get up and to walk without a splint a couple of days later. The unhampered movement is started a long time before the fracture cleft is bridged over by bone, even before the least beginning of callus formation is observable.

This means that the so-called "after-treatment" with massage, heat, etc. is not necessary because it is superfluous. The damages resulting from the fixation such as atrophy of the muscles, stiffening of the joints, etc. do not occur at all. Even the injuries of a prolonged confinement to bed which are so much feared with old people do not occur any more: impairment of the general circulation with the danger of the development of pneumonia and at the same time of decubitus. Even the circulation within the extremity is not hampered. This may explain why in marrow nailed leg fractures edema is less frequently observed which in many cases treated otherwise creates such a complicated situation that many months and even years are necessary to heal them. Even after the lapse of a long period of time they may not subside. This is all the more important when taking into consideration that edema always occurs after the use of plaster casts and the traction method.

Finally, the psychic influences upon the patient must be considered. When using the marrow nail method a patient suffering a thigh fracture is relieved of the depressing feeling of being confined to bed for 10 or 12 weeks in a supine position. In this way he no longer thinks of himself as being seriously injured and there can be no doubt about the favorable influence on the psychological factors associated with the healing process. For a surgeon who has treated many thigh fractures it is a great satisfaction to see how patients who have suffered thigh fractures are lying in bed in a normal lateral position without pains, sometimes only a couple of hours after the nailing operation and to observe them moving the limb a very short time later. The pains at the fracture site subside due to the stabile fixation. We know that contrary to a luxation, a fracture is painful only when moving the limb and movements of that kind cannot be prevented even when a plaster cast or traction treatment is used. All this is of special importance in connection with changing the bed, use of the bedpan, etc.

The nursing care of the patient is considerably facilitated and shortened because the patient may get up early.

There is no other method, no matter whether it is conservative or radical, by which the fragments may be held in position so strongly. Even in the unpadded tightly fitting plaster cast considerable movements of the fragments against one another are possible because layers of soft parts lie between the cast and the fractured bone which may be shifted more or less. In case of the thigh these soft parts have a diameter of 20 - 25 cm. with the diameter of the bone being only about 3 cm. Furthermore we must consider the hematoma and the edema. If these subside a couple of days later, and when the unavoidable atrophy occurs, the conditions for a possible displacement are much more favorable. In comparison to other methods the traction bandage is the least suitable for keeping the fragments in place.

The fixation of the fragments is so enormously strong that even the slightest wobbling movements, the so-called "millimeter-movements" are completely absent. This is of utmost importance for the healing of the fracture. In the cleft of each fracture a young germinating tissue grows and to its greater part it is formed by periosteum as a preformed connective tissue bone.

The periosteum alone cannot achieve that. The callus is constructed by the bone substance because of the stimulating effect of the trauma. The marrow nail itself may also stimulate that effect either chemically or mechanically. In this first phase of the healing process a shifting of the ion equilibrium to the acid side takes place due to the mechanical inflammation resulting from the trauma and the decay of tissue. This is not observed later during the second phase in which the callus becomes basic. At that moment the deposition of calcium begins and the callus becomes stronger. This young bone and particularly the growing callus are extremely sensitive to even the slightest harmful mechanical strain. If in the fracture cleft the distraction forces, or those which cause lateral displacement, prevail, a bony healing of the fracture cannot be expected and a pseudarthrosis will develop which causes the failure of all our efforts (Chapter III). According to these theoretical considerations and also according to our practical experiences, pseudarthroses are more frequently observed with the traction method. With the use of the marrow nail, however, callus may develop completely unhampered and well protected against harmful mechanical forces. This may be well observed microscopically as was proved by GRIESSMANN and REICH in animal tests. Due to the wobbling movements in the cast or traction bandage the bone spicules represent a badly arranged system whereas in the case of marrow nailing all spicules run absolutely systematically "as if they were drawn by use of a ruler". In case of a successful marrow nailing a pseudarthrosis will not occur and consequently the marrow nailing method is the method of choice for treating a pseudarthrosis (Chapter IV).

The complete and absolute immobilization of the fragments is of utmost importance to prevent the development of an infection or its spreading (Chapter IV). Therefore this method may also be applied to the treatment of compound fractures and even to gunshot fractures (Chapter VII).

In this connection it is important that the immobilization of the limb is not interrupted by extracting the nail if a suppuration develops. It has been proven that the suppuration is not caused by the nail, on the contrary, in case of an infection the wounds above the nail heal quickly and foreign bodies of immense proportions heal in as soon as the sequestrum or the abscess of the soft parts (which caused the inflammation) is removed. In such a case the fracture cleft as well as the nail insertion site must be kept open in order to facilitate the draining off of the pus. The marrow nail acts as a drain which drains the bone from the inside. We must take into consideration however, that this tube is made of steel and that it is lying in the marrow cavity. It has been proven by experience that in the long run the presence of the marrow nail in the marrow cavity has no harmful effect on the healing process.

In simple fractures an infection may easily be avoided by the fact that only a small stab incision is required for insertion of the nail. Necroses of the soft parts and buried suture lines are not frequently observed.

The nail must be inserted, so to speak, precutaneously and the fracture site must not be exposed. Therefore the nailing is described as a "percutaneous marrow nailing" or "closed marrow nailing". BOEHLER and HAEBLER call it a "covered nailing". The stab incision is made at some distance from the fracture cleft (30 centimeters and more). Therefore an infection of the fracture cleft occurs less frequently than in fractures treated operatively. According to the statistics of REICH, injuries caused by infection are less serious in nail treated fractures than in fractures treated conservatively. All this must be ascribed to the fact that fractures treated with a plaster cast or traction method are not spared the hazard of infection because of the suppuration of decubitus spots and the infection of the wire insertion sites (Chapter IV).

This advantage does not exist of course when using the marrow nail with an osteotomy (open method) because in that case the bone or the fracture cleft must be exposed. The advantage of the absolute stability of the osteosynthesis and the possibility of subjecting the limb to early movements do prevail however. The marrow nailing is of greatest advantage in those cases in which corrections must be made in deformities acquired by accident, disease, or in congenital deformities. Only by use of the marrow nail method do several surgical interventions become useful operations, as for instance the lengthening of the lower extremities or the shortening of the forearm.

The nail does not simply replace the hitherto known screws, wires, plates, etc., but we have to deal with a new principle in the technique of the osteotomy. It is quite possible to abandon v. LANGENBECK's principles of the subperiosteal operation. The separation of the periosteum, for instance, is urgently required for the application of LANE's plates. The vessels necessary for the nourishment of the bone are located in the periosteum and greatly contribute to the formation of callus. When applying the principles of the marrow nailing, however,

damage to the periosteum is avoided because it need not be separated from the bone and the surrounding musculature because the fragments are united from the inside of the bone (Chapter VI).

Consequently the operation in question is only a small operation. This fact is very important because each damage of the tissue by an operation means a further shifting of the ion equilibrium to the acid side. When considering the fact that such a shifting takes place anyhow, because of the existence of the fracture, we have to deal with an accumulation of disadvantageous effects which may result in the development of such acid vallues as we usually find only with secondary healing and its associated effects upon the soft parts (SCHMIDT, GOETZE, and BRACKERTZ).

The marrow nail operation has proved its value also in connection with the intentional artificial stiffening of the joints. A small stab incision suffices to get an immediate absolute fixation of the joints.

Some research work has already been done to form artificial joints with the marrow nail (Chapter IX). On the other hand the new method has proved its value in spontaneous fractures which are due to inoperable tumors and metastases. A healing of the disease could not be obtained but its main symptom, the fracture, could be eliminated even in those cases in which there is no hope for a bony bridging over of the fracture cleft. For the rest of the patient's life the nail replaces the mechanical funtions of the bone. For a long period of time the patient may even live under the impression of being healed. In any case the patient need not live with a dirty pelvic cast for the remaining months or years of his life, and this is particularly true in all those cases in which - as usual - the tumor is located subtrochanterically. On the other hand there are also better conditions for heliotherapy (Chapter VII).

In the two latter cases mentioned above the nail must be left in the bone. In all the other cases it must be extracted after a lapse of some months, i.e. after the healing (Chapter V).

All this means that the field of marrow nailing extends far beyond the treatment of fractures into the field of surgery and orthopedics. Transverse and oblique fractures of the shaft belong to the limited field, compound fractures of the upper extremities are well suited for the nailing method, compound fractures of the lower extremities, however, are only exceptionally suitable (Chapter V and VII). Fractures of the joints or near the joints and fractures of the short flat bones are not suitable for nailing. In order to underline the importance of the marrow nail method I would like to refer to the following publication by EUFINGER, HERZOG, and HENCK of the University of Kiel:

From 1 January 1944 to 1 May 1946, 1,125 cases of fractures were treated. Of this number, 755 fractures must be excluded because in all these cases we were not dealing with shaft fractures but with fractures of the spine, radius fractures and fractures of the joints, fractures of the neck of the femur and the head of the tibia. We excluded also portrochanteric fractures despite the fact that fractures of that kind may also well be treated with the marrow nail method. At the same time fractures of the head of the arm above the elbow which now are also frequently nailed were not included in the statistics.

Consequently we have to deal with 1,125 less 755 = 370 fractures, 155 of which were treated with the nail method and 215 of these cases were unsuitable for various reasons including 50 fractures in children. In children younger than 14 years treated conservatively, a stiffening of the joints or general or local injury of the circulation are not observed so that the most important advantages of the marrow nail method are not important in these cases and it is applied only exceptionally (Chapter V). Furthermore 36 cases had to be excluded from the very beginning because they came to fatal terminations within a couple of hours or days after the accident and a few cases were not included for various reasons (fractures of the joints or near the joints, serious shock, etc.) to which reference is made in the following statistics:

Table I

At the Kiel clinic from January 1st, 1944, to May 1st, 1946, 204 cases out of 370 cases of fractures of the long shaft bones were not nailed for the following reasons:

Reasons	Thigh	Leg	Arm above elbow	Fore-arm	Total
Fatal termination a few hours or days after the patient was hospitalized because of secondary injuries or shock	14	3	2	5	24
Primary amputation	2	8	-	2	12
Serious shock or other injuries	5	4	-	3	12
Skin infections or suppurating wounds of the extremity	-	1	-	-	1
Joint fracture	1	16	1	-	18
Fracture near the joint	9	20	7	-	36
Comminuted fracture	7	7	4	-	18
Osteomyelitis	-	-	1	-	1
Fractures in children younger than 14 years	24	22	1	3	50
Interruption of the nailing operation because a reduction was not possible	1	3	3	-	7
Infraction (incomplete fracture)	-	6	1	4	11
Nailing operation refused	-	1	-	-	1
Information no longer available	1	10	1	1	13
Total	64	101	21	18	204

Particulars concerning the Stable Fixation.

The union of the fragments obtained by the marrow nail is enormously strong. It depends on the thickness of the nail of course and its diameter must correspond to the diameter of the marrow cavity. The thigh nail is considerably thicker than the leg nail and consequently its stability is also much stronger. (This refers to the different mechanical properties of the marrow nails with regard to the different bones). The resistance of a nailed fracture to forces causing lateral displacement amounts to several thousand kilograms. It is a matter of course that this power of resistance will in no case be exhausted or surpassed because the forces normally arising there amount to only a fraction of this amount even if the thigh is subjected to strenuous use. The resistance of the nailed fracture against angulation depends on the shape of the fracture. It is considerably stronger than the stableness of the nail itself. The bone acts as though lashed to the nail by virtue of the fact that after the nailing the fracture cleft is only a fraction of a millimeter wide. When angulating a nailed fracture the fragments must be pulled apart in the axial direction of the nail. In this case the tension of the entire musculature of the limb must be overcome which may amount to several hundred kilograms because the flexor and extensor as well as the adductor and abductor all act in the same direction, i.e. in the axial direction. At the same time, however, the friction of the nail in the marrow cavity must be overcome, which during the first weeks may also amount to several hundred kilograms according to the relation of the diameter of the nail to the diameter of the marrow cavity.

The resistance against angulation of the thigh nail itself amounts also to several hundred kilograms, according to its length and diameter. Its resistance against angulation is therefore very great. In general, values of that kind can be observed only in the thigh when jumping from high altitudes.

The resistance against displacement of the fragments in the axial direction of the nail is in general very considerable and it depends on the relation of the diameter of the nail to the diameter of the marrow cavity. Therefore the nail should be as wide as possible because the union of the fragments obtained by the nail is strongest. On the other hand, however, a nail which is too wide will render the nailing operation impossible.

This is the only possibility for a failure of a Marrow nailing (excepting those cases in which the fracture is unsutiable for the nailing operation due to the location of the fracture site or the shape of the fracture or the site of an osteotomy).

These possibilities may be excluded from the very beginning by careful study of the X-ray. Consequently all those cases in which the marrow cavity is too narrow should be exempt from the nailing or a thinner nail should

be used and consequently we must forego early ambulation in these cases. At the clinic of Kiel the marrow nailing was used in every case. We rather preferred to use a thinner nail, which, however, was necessary only in three cases of thigh fractures. The surprising thing is that in adults the marrow cavities of the thigh and of the arm above the elbow are all about the same diameter, whereas in the leg considerable variations are found. The marrow nail should forge a stabile union with the marrow cavity.

When we started marrow nailing the nails were constructed somewhat wedge-shaped so that they tapered in the direction of the nail tip. Later on we found out that this tapering was superfluous. The two-lamella nail has great advantages in comparison to the three-lamella nail. Its diameter is V-shaped. The two sides of the spring-like "V" are pressed together during the insertion into the marrow cavity and in this way the nail fits the different diameters of the marrow cavity. The manufacture of these nails is considerably less expensive than the nails for the neck of the femur which are machined from a solid piece of metal because the latter must be manufactured by the milling process. The thickness of the sheet metal used for marrow nails is 1.2 - 2.2 mm. according to the thickness and length of the nail required. The force with which the bone fragments are held together in order to avoid displacements in the axial direction depends largely on the length of the nail. In adults the nails are 23-42 cm. long according to the location of the fracture. The nail should extend at least 6-8 cm. into the distal fragment. In knee arthrodesis, nails of 60 up to 65 cm. length are required (Chapter VIII). The force required to insert the nail in the axial direction is multiplied considerably in the transverse direction. We must, however, subtract the friction which is likewise considerable. The marrow cavity is not a simple cylindrical tube with smooth walls, but it shows numerous irregularities, projecting spots and edges which must be overcome when inserting the nail and which give the nail its strong hold in the cavity.

In general the hold of a freshly inserted marrow nail is considerably stronger than a nail for the neck of the femur due to the following facts:

1. The marrow nail is located in the extremely hard and barely flexible compacta tube whereas the nail for the neck of the femur is surrounded by the relatively soft spongiosa.

2. Due to the fact that it is V-shaped the marrow nail which is somewhat flexible, forges a stabile union with the bone.

3. The nail for the neck of the femur is kept in place by the friction of the spongiosa of the neck and the head which is shifted aside.

4. In all cases the marrow nail is considerably longer than the nail for the neck of the femur.

5. In many cases the marrow nail is somewhat angulated whereas the nail for the neck of the femur is straight, (exceptions from the latter rule are only those cases in which the nail becomes somewhat angulated because of faults in the material).

The marrow nail is not only elastic in the transverse but also in the longitudianl direction because of its V-shape.

In thigh nailing operations the inflexible nail is no obstacle if the marrow cavity is somewhat angulated. I would like to point out once more, however, that the only obstacle to be overcome is the disproportion of the diameters of the marrow nail and of the marrow cavity.

KUENTSCHER has called this new method "marrow nailing" and he does not want to use the word "bolting". Due to the above described elastic forces the fragments are kept together in much the same way as a carpenter's nail holds two pieces of wood together by elàstic forces. Only in this way is it possible to protect the fragments against displacement which is quite different from the bolting method.

Marrow nails are made of V2A steel, the only metal able to stand the high mechanical strain to which it is subjected. The strain upon the nail for the neck of the femur is much greater of course. The nail for the neck of the femur stands more or less vertically to the lines of force and consequently it is subjected to those forces causing lateral displacement and angulation. So, in cases of early weight bearing we sometimes see fractures or angulations of the nail. In case of a marrow nailing the strain upon the nail is less because it is not subjected to so much force causing lateral displacement and angulation and furthermore, it lies in the direction of the lines of force. In the thigh, conditions are very favorable for the insertion of a straight inflexible nail which may be driven in from the trochanter. In the arm above the elbow and in the leg the marrow cavity must be exposed laterally above or below the fracture site by means of a drill and through the hole made in this way a flexible nail must be driven in.

It is obvious that one can fix a broken tube-like body by inserting a stabile stick. From the technical point of view this method represents the strongest reunion possible. In the first place, however, this effect is much more easily obtained than by applying a short sleeve which in order to grant good stability must fit precisely in the cross-section. An inserted stick, however, need not fit that precisely.

Even by using steel such a stabile device can only be inserted into the marrow cavity if it is able to hold the fragments together without additional support. Such a device must be of considerable size if it is to grant sufficient stability.

It is characteristic for this method that - almost automatically - ideal reduction is obtained and in most of the cases the former anatomical form of the bone is restored. In general such good results cannot be obtained by other methods which can easily be proved by the numerous illustrations published in Chapters V, VI, and VII. We must, however, not attach too much importance to this point because a healing with a lateral displacement of even as much as the width of the shaft is of no importance. The most essential part, however, is the correct axial position because according to BOEHLER angulations of the thigh bones of 10° may cause disturbances of the joint functions.

Economic Advantages

From the economical point of view marrow nailing is better than all the other methods. This is true not only with regard to the duration of hospitalization but also to the duration of disability and the number and amount of disability awards. HAEBLER was first to publish statistics concerning the economic advantages of the new method.

BOEHLER who is well known for his excellent results has, in 1929 and 1934, checked 14 of his own cases of simple thigh fractures which were treated either by means of plaster casts or traction bandages. All patients were members of the Workmen's Insurance Company against accidents and the time of treatment amounted to 240 days on an average. In 18 patients who had suffered thigh fractures and who were treated in other hospitals by order of the same insurance company the treatment lasted longer, even 340 days.

In HAEBLER's cases of thigh fractures which were treated by means of the marrow nail method the time of treatment lasted only 53 days on an average, in the last three cases only 35 days. This means that when taking a daily allowance of 5.-- RM per patient as a basis, 200-300 days of hospitalization or 1,000 to 1,500 RM per patient were saved by the insurance company.

In BOEHLER's own cases of thigh fractures which were treated by means of plaster casts or by the traction method the disability lasted 627 days on an average, while in the cases treated in other hospitals it lasted even as long as 1819 days.

In HAEBLER's cases of thigh fractures which were treated by means of the nail method the duration of disability lasted 97 days on a maximum. In that case the time required for the extraction of the nail (the patient was 60 years old) is included. In comparison to BOEHLER's cases which were referred to above, the results obtained by HAEBLER represent a saving of 1½ years.

In only 5 out of 18 cases of thigh fracture treated by other methods in other than emergency hospitals was the decrease of the capacity to earn a living less than

20 % (according to the same statistics). That is less than 1/3. In only two patients was the employability completely restored.

All cases of thigh fractures treated by HAEBLER were free from symptoms. The conditions were similar in leg fractures and in fractures of the arm above the elbow.

The results obtained are summarized in the following statistics:

Table II

Economic advantages of the marrow nail method

Simple thigh fractures

A. Plaster cast or traction bandage:

	Duration of treatment on an average (days)	Lost working days on an average	Permanent disability in %
Cases treated in emergency hospitals	240	627	10.2
Treated in other than emergency hospitals	390	1,819	22.6

B. Marrow nailings:

Duration of treatment on an average (days)	Maximum loss of working days	Permanent pensions
53	97	0

Table II: Comparison of the duration of treatment, lost working days and pensions in cases of simple thigh fractures. Admittedly good statistics (by BOEHLER) and marrow nail statistics (by HAEBLER) were used.

Publications by H. GRIESSMANN and W. SCHUETTENMEYER from the clinic at Kiel show similar results.

In simple thigh fractures treated with the marrow nail method the period of hospitalization amounted to only 40 days on an average. In simple leg fractures the period of hospitalization amounted to 34 days on an average. In this calculation is included one case of a most serious arthrosis of both ankle and knee joints (120 days) and 2 cases of delayed formation of callus with secondary healing (120-150 days) which influenced the statistics unfavorably. Without these three unfavorable cases we have to deal with a hospitalization of 29 days on an average. The hospitalization in the clinic itself amounted to ten days only and after that time it would have been possible to release the patients for ambulatory treatment. Because of the constant air-raids, however, the patients preferred to be brought to an auxiliary hospital, outside Kiel and they stayed there 24 days on an average (respectively 19 days for leg fractures). Late examinations could not be made because of the conditions of war.

For the same reasons only 22 out of 42 patients who suffered simple leg fractures could be examined once more. 18 out of these 22 cases or 82 % were free from symptoms. In the remaining 4 cases we had, first of all, to deal with a woman patient who suffered an arthrosis deformans. Secondly a 65 year old patient suffered pains at the fracture site 1½ years after the operation. Objective swellings of the soft parts and a muscle atrophy of 2½ cm. of the leg were observed. Besides these symptoms he suffered from an anklebone fracture so that an additional plaster cast had to be applied. The fracture had come to a bony healing. In a third case we had to deal with pains which were not due to the nailing operation (varicose veins). Objectively there were no symptoms of a disease. In the fourth case with a fracture in the lower third a stable osteosynthesis could not be obtained (see Chapter V). Also in this case we had to deal with an additional ankle fracture so that the application of an additional plaster cast was indicated. Five months after the accident the late examination proved that the fracture was clinically healed. There did exist, however, slight disturbances of circulation in the leg.

The late examination of the leg fractures proved in none of the 22 cases (with exception of the one case in which a measurable muscle atrophy existed) did a limitation of the respective limb exist. With exception of the two cases mentioned above no abnormal edema of the soft parts or other disturbances of the blood circulation were observed.

In the 180 fractures of the arm above the elbow the duration of hospitalization amounted to 11 days on an average. In all cases a bony healing was achieved.

Late examinations revealed that with the exception of one case not even the slightest impediment of neighboring joints or muscle atrophy existed.

That exception refers to an 87 year old patient whose shoulder rotation was limited to 2/3 who, however, was able to cut wood every day.

In 10 out of 16 forearm fractures the radius and the ulna were broken. In 6 out of 16 cases the fracture site had to be exposed because of the difficulties encountered with the reduction. In most of the cases we had to deal with old fractures. The period of hospitalization amounted to two weeks on an average in all simple fractures. In all cases in which the fracture site was not exposed it amounted to only 5 days. Many patients resumed light work 7 days later.

With only one exception all cases came to a bony healing. In that case we had to deal with an ulna fracture in a locksmith who four weeks after the accident had resumed heavy work and broke the nail which event must be blamed for that failure.

In one case the formation of a large bridge callus was observed so that forearm rotation was entirely eliminated. The bridge callus was removed operatively and a fat lobe was inserted. After that the rotation was possible though considerably restricted.

In a 60 year old patient who could be nailed only 10 days after the accident because of shock, many wounds were observed in his face. After one abscess in the face had drained off an abscess of the nail insertion site was observed one month after the marrow nailing (Chapter IV). After that disturbances of circulation of the soft parts and a Sudek-atrophy of the forearm bones were observed. The fracture came to a bony healing, however, the rotation of the wrist was limited. In all the other patients the late examination revealed that muscle atrophy and limitations of the joints did not exist.

In no case did the insurance companies pay any pensions. The 60 year old woman mentioned above was not entitled to receive any award. In the patient with the fracture of the nail the treatment had not yet come to an end, because a second nailing operation was indicated. There is no doubt that he resumed working too early.

In comparison to statistics on the conservative treatment, the period of hospitalization in cases treated by the marrow nail is much shorter even in compound fractures and the employability is restored more quickly. In this connection I would like to refer to Chapter VII about marrow nailing of simple fractures.

CHAPTER III.

The Biological and Physiological Background of Marrow Nailing.

When studying a new method for the treatment of bone fractures it is absolutely necessary to study its influence on the healing process in the fracture. A bone fracture is healed as soon as the fragments are bridged over by stable bone (callus). This "bridge" must be built by the body itself - a very complicated procedure. The only thing we can do about this is to help the body by seeing to it that the fragments are in good position, furthermore that all disadvantageous effects are prohibited and any impediments that develop are eliminated. These are the decisive facts when considering the therapy. We know that the young tissue developing in the fracture cleft may be hindered so much by certain harmful effects that callus does not develop. This means that the fracture does not heal and at the end of our endeavors we have a pseudarthrosis.

Furthermore we know that the same damaging effects may even cause the destruction of sound bone. The knowledge of these processes in adult bones is of special importance in connection with the understanding of the processes taking place in the callus.

A. Anatomy and Function of the Bone.

The main function of the bone system is to grant a strong frame for the body. Each bone is constructed for pressure and has in part to fulfill static functions. In most cases, however, those bones are supports on which the traction forces of the muscles act. In this way, by the traction of a single muscle and at the same time by the total muscle mass surrounding it, the bone is subjected to strain in the longitudinal direction. In this case the traction forces act in such a way that the bone is subjected to pressure which must be considered to be acting at the joints. This type of strain is known to technicians as "Zerknickung" (a force tending to produce destruction by angulation; as a bridge girder buckles under an excessive load, a bone will fracture with angulation). The pressure of the muscles is much stronger than the static strain of the body weight. It is well known that a precise movement of a limb in a joint requires a simultaneous action of the antagonists so that strong forces causing pressure are developed. O. FISCHER for instance observed that the force which presses the joint ends of the elbow joint together amounts to several hundredweights when half a hundredweight is lifted. According to the findings of KULTKRANZ that pressure amounts to 20 - 21 kilograms, if the weight to be lifted equals 2 kilograms. In comparison to this the dynamic strain of the body weight on the bone when running or jumping is of minor importance. It is a matter of course that the bone also has to resist all possible oblique or transverse forces acting on the bone and it would do that too if it had another shape. Its function and structure, however, are determined only by the maximal forces acting on it.

The Deformation of the Bone when under Strain.

Despite the fact that the bones are the main framework of the body we must not come to the conclusion that the bone itself is an absolutely stable structure. On the contrary, every function of the bone presses the bone together and causes its deformation. Due to the fact that the bone is absolutely elastic it regains its former shape as soon as the strain on it is below the limit of elasticity. If that limit is surpassed, the bone will break. The deformation of the bone is very slight and amounts to only some fractions of a millimeter. Due to the fact that these deformations are so slight it has so far not been possible to measure them on the bone itself. In order to get an idea of the deformation the anatomist W. ROUX constructed some rubber models and covered them either with paraffin or stearin. As soon as the bone is subjected to strain the cover shows clefts at the spots of strongest impact. The disadvantages of this method are absolutely clear. It is not possible to construct a rubber-model which fits the bone because we cannot model the inner bone.

Therefore this author did not use rubber models, but bones decalcified by acid. During the decalcification process the bones become so soft that the deformation was much more marked. This was easily noticed at the spots of impact. Furthermore we succeeded in impregnating those decalcified bones intensely with metal salts so that the deformation of the trajectories inside the bone were also quite visible. (Illustration 2)

a Illustration 2 b

Decalcified bone impregnated by metal salts.

a) normal (KUENTSCHER) b) under strain

This method as well as that of ROUX is characterized by the disadvantageous fact that the deformations appear too marked so that we cannot find out the true deformations

of the bone under strain. These deformations are so extensive that even the points of application of forces are shifted in relation to each other. Besides that we are interested in finding out the true amount of deformation and so it can be put to practical use. In 1914 HANAUSEK, when dealing with ROUX's method said: "The best method to determine the deformation and the forces causing deformation is to use living bone. The difficulties encountered in this respect were however insurmountable so far".

The author studied all available technical methods in order to find a way to apply it to the bone in order to be able to show the real deformation of the bone when it is subjected to strain. Finally he came to a method developed by DIETRICH and LEHR and which is used in aircraft construction and which seemed to suit best. Amazingly enough this method is somewhat similar to ROUX's method. Finally the author developed the following method:

The bone to be studied should be coated with a special varnish, synthetic resin or resinoid. This coating has a high adhesive power so that it is not detached from the bone if the deforming force exceeds the limit of the elasticity of the bone. The elasticity coefficient of the coating is considerably greater than that of the bone, while its tractility (while subjected to bending) is very small. If at any place of the bone surface traction is exerted which cannot be withstood by the firmly attached coating as a result of its small expansibility, fissures appear in the coating. These fissures, or cracks, which appear as soon as the burden placed upon the bone exceeds a certain limit value, are traction cracks. After a large number of thorough investigations the author found that liquefied resin proved best. With this material it is possible to demonstrate the above mentioned properties by preparing a thread of 2 M. length, this can easily be accomplished by stretching out the liquefied material. Such a thread breaks if it is being increased in length by traction; this happens when the expansion is 0.2 mm for 2 M. or 0.001 mm for a distance of 1 mm. Thus it is quite possible to make the experiments with the smallest possible weights, i.e. with such a strain which occurs normally. On the other hand the coating is so flexible that it can follow any bending of the bone. A piece 20 cm. long and 1 mm. thick may be bent so much that a semi-circle is formed which cannot be done with a piece of bone equal in length, even if it originates from a juvenile individual. It is of the greatest importance that the fissures appear even with a strain which is far below the elasticity limits of the bone. Thus the bone is studied as it reacts under normal conditions. It is sufficient to put a weight of 26 kgs. upon the femur head of an adult of 70 kgs. body weight to produce the cracks on the neck of the femur. Here one must bear in mind that the static pressure exerted upon the same femur during slow walking when the entire body weight is placed upon the leg is equal to the body weight minus the weight of the thigh, or more than 30 kgs. The fissures can be produced by simply exerting a pressure with the hand it is most amazing to see the bone suddenly covered with a regular system of traction cracks (see Illustration 3).

a Illustration 3. b

Traction cracks of the femur according to KUENTSCHER.

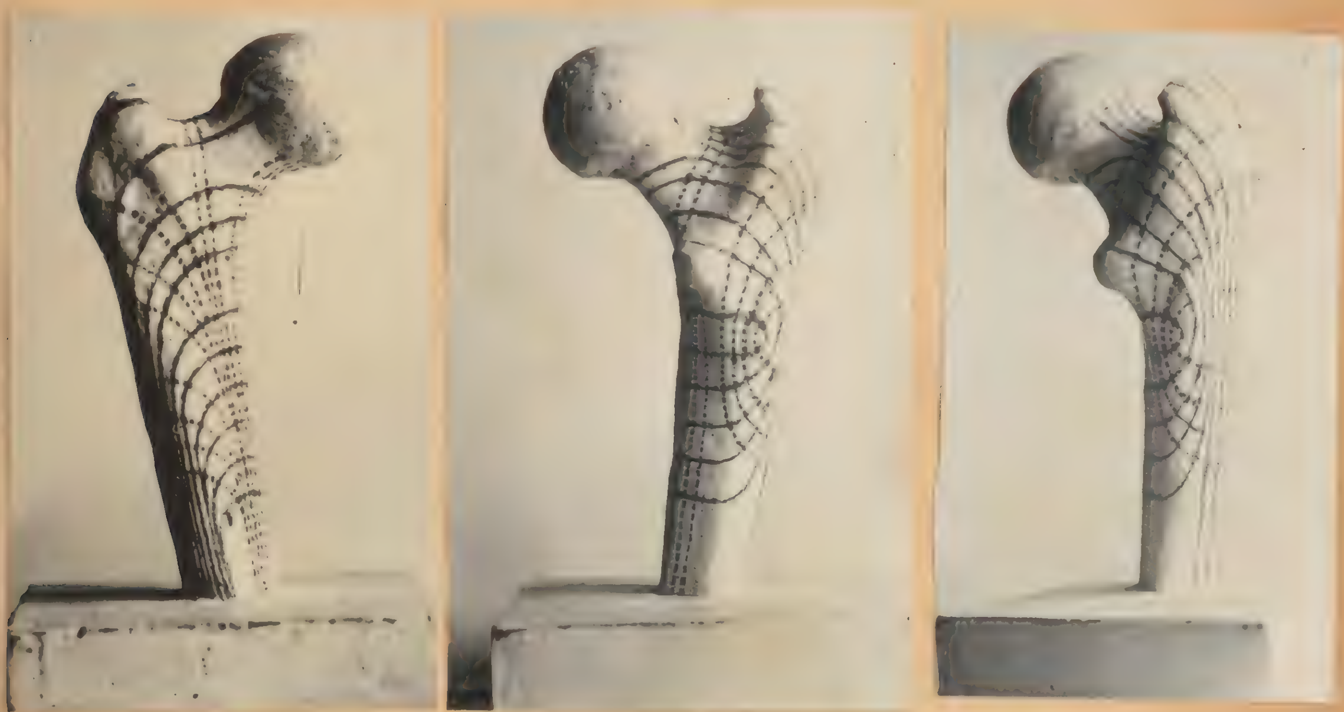
a) with a slight pressure upon the femur head

b) with a heavy pressure upon the femur head. (front side)

c) same as b, rear side.

Such a demonstration of the expansion taking place in the femur is at the same time a demonstration of the force in action, since according to HOOK's principle the expansion is directly proportional to the force effecting it. The places of the greatest expansion of the bone, therefore, are the places of the maximal tension, the socalled "Spannungsspitzen" (tension maximum). The traction cracks which appear first after subjecting the thigh to weight bearing show the tension maximum. They correspond to the cracks displayed in Illustration 3, at the neck of the femur and below the trochanter major. In these places where the greatest degree of traction is found the varnish coating breaks always vertical to the direction of the traction force, as the cleft in the coating is a transverse fissure. The tension maxi-

mum is located at the places indicated in Illustration 3. The compression forces can be exhibited by the reversal of the procedure. This can be effected by subjecting the bone to weight bearing before the coating has tempered. After tempering the bone is released from weight bearing. Subsequently at the places which were subjected to pressure and where the bone substance was compressed the bone expands and thus causes cracks in the varnish coating. By these means one can exhibit the compression forces and the tension maximum of the compression force. The first method is applicable to static and dynamic deformations, the second one to static deformations only. Finally both procedures may be used simultaneously. In the first place the compression cracks made visible through the release of the pressure are shown. Then the same preparation is subjected to weight bearing once more with the result that the traction cracks appear on it as well (see Illustration 4.).



a) frontal view b) dorsal view c)dorso-lateral view

Illustration 4.

Compression and traction cracks on the femur (according to KUENTSCHER) appearing after pressure upon the head of the femur.
The solid lines indicate the traction cracks, the broken lines indicate the compression cracks.
To demonstrate the forces provoking the phenomenon, according to what was explained above one only needs to draw a perpendicular line upon the traction or compression cracks (which actually are the fissures in the varnish coating). Since the traction and the compression cracks are vertical to each other we also can describe them as lines of force. In this case the solid lines indicate the pressure forces, while the broken lines indicate the traction forces.

This demonstration recalls the famous "crane-theory" of the thigh proposed by MEYER-CULMANN. According to this theory the trabeculae in the neck of the femur correspond to the tension trajectories in a similarly bent crane which is subjected to weight in much the same way (see Illustration 5).

Tension trajectories in the thigh according to MEYER-CULMANN. A considerable difference is quite noticeable. CULMAN's demonstration is based on calculation but only in the most simple geometrical bodies a calculation of the course of the lines of forces is possible. A calculation of that kind is entirely impossible in bodies with a complicated external form as for instance bones. Furthermore it must be taken into consideration that the "internal structure" of the bone i.e. the trabeculae of the spongiosa can by no means be defined by calculations. Therefore the famous "crane-theory" of the thigh by MEYER-CULMANN must be considered only as an attempt to give at least an idea of the propagation of the force in such a body. The body calculated by CULMANN was a simple round stick curved like the thigh bone, which is subjected to a static weight at its tip. The traction crack method, however, accurately demonstrates the actual propagation of the forces in the bone and moreover it indicates the location of the greatest tensions. Even though it only exhibits the conditions on the surface it nevertheless is indicative for the entire bone, as the bone in its greater part is a hollow body. Wherever it contains osseous substance in its interior, nature itself shows the propagation of force because it is a matter of course that the force necessarily must follow the trabeculae.

Illustration 5.

In all these tests the propagation of force in the bone, the so-called "Kraftfluss" (flow of forces) was demonstrated while the bone was subjected to the above described principal strain that means while pressure was exerted on both joints in the longitudinal direction. In this way the following very important facts were found: The force does not flow equably through the bone, but only in certain lines. In some places the lines are crowded together and so we have to deal with accumulations of tension: The so-called tension maximum. In order to facilitate the understanding of the processes in the bone the demonstration of the course of these lines and the location of the tension maximums is of utmost importance for two reasons: 1) If there are any pathological changes of the bone caused by mechanical conditions their location and direction must correspond to the

location and course of the tension maximums. 2) The illustration of the lines of force will be of great help to facilitate the understanding of the bone structure, for, if this structure depends on the function, as presupposed, it must correspond to the lines of force. It is the function of the bone to transmit the force and to resist it. The author was in a position to prove that the course of the trajectory lines and their extension in the compacta of the "osteogen columns" corresponds to the lines of the maximal forces.

Illustration 4 reveals as a second amazing fact that any pressure on the neck of the femur causes the appearance of additional forces. On the superior surface of the femur neck and on the lateral aspect of the shaft strong traction forces occur. On the other hand also on the inferior surface of the femur neck and on the medial aspect of the shaft traction forces can be observed which in this case act as transverse forces just as in the places where the greatest traction tension is observed, pressure forces occur as additional forces acting in the transverse direction. If one coats the femur with a resin coating and then places a gradually increasing weight upon it, the first traction cracks are found on the surface of the femur neck indicating that this is the place of the traction tension maximum. Later on a second traction tension maximum develops on the lateral aspect of the femur shaft, located somewhat below the trochanter minor. Finally the coating of the entire bone is covered by a system of cracks and it is quite noticeable that at the place of the highest pressure tension the traction cracks develop as well. These traction cracks run always vertical to the pressure cracks. According to what was explained above the traction tension (traction force) always acts vertical to the cracks produced by traction, the former being represented in Ill. 4 by the broken lines. The pressure tension (pressure force) acts vertical to the cracks indicating it, and they are represented in the Illustration 4 by the solid lines. In most of the places two different tensions which are vertical to each other are found and a bi-axial tension is to be observed in the bone. The fact that there is a bi-axial intraossal tension is of the utmost importance for many problems related to the strain placed upon the bone. As it was mentioned above one can prove that the osteogen columns correspond to the direction of the maximal traction and pressure forces and that the course of the trajectories is also exhibited in the illustration, as their extension to the surface (the only place where they can be made visible with our method) corresponds to the tension maximum. The first traction tension maximum is located at the place where the curved column of the trabeculae comes to the surface of the femur neck, while the second one is located at the terminal of the former. The pressure tension maximum is located at the terminal of the straight column of trabeculae. It is interesting to note that the course of the lines of force on the anterior aspect is different to that on the posterior surface where there is a whirl of lines of force.

Other than the detection of the sites of highest tension this method reveals nothing about the correct order of magnitude of the traction and tension. The local deformations of the bone are so minimal that so far at least it has not been possible to demonstrate them. In the last years methods have been developed in Sweden, Switzerland and then also in Germany which made it possible

to measure deformations of that kind very accurately. The mirror-method of MARTENS is not applicable for the bone because the deformation involves the entire bone and consequently there is no fixed point on the bone, on which one can attach the measuring telescope. Excellently suitable however is the tensometer by HUGGENBERGER and the extension meter by OKHUIZEN. Technically both instruments are based on the principle that the deformation of a certain measured length is transmitted by means of a lever in a strongly delayed action. At the same time we have available the extension meter by MAYBACH. The author uses the extension meter by OKHUIZEN constructed by STAEGER with an accessory which allows the use of measuring scales of either 10 or 20 centimeters. The instrument is very small and handy, it weighs about 70 grams. It must be put upon the bone by means of its two steel blades and it is pressed against the bone by a clip. In this connection it is important that the pressure which holds the instrument against the bone is only slight. The instrument reacts upon slightest variations of tension in the bone, and multiplies by 1000 the variations of the length of the measured distance. This degree of enlargement suits best for most bone tests. A mirror is attached to the scale of the instrument for reasons of parallaxis and the precision of measurement amounts to 0.1 %. When reading the instrument we have to use the estimated 1/10 of the interval as a unit. It must be taken into consideration however, that the instrument does not function with the blades in a horizontal position but with the blades in almost vertical position. Consequently tests must be arranged in such a way that the instruments used may be revolved. It must be said, however, that the use of this instrument requires some skill and practice. There is hardly any danger that the blades might penetrate the bone substance too much and consequently result in false values. The instrument measures the straight distance between the two blades. This must not be forgotten when studying the final measuring results in all those cases in which the instrument was applied to curved planes (see Illustration 6).

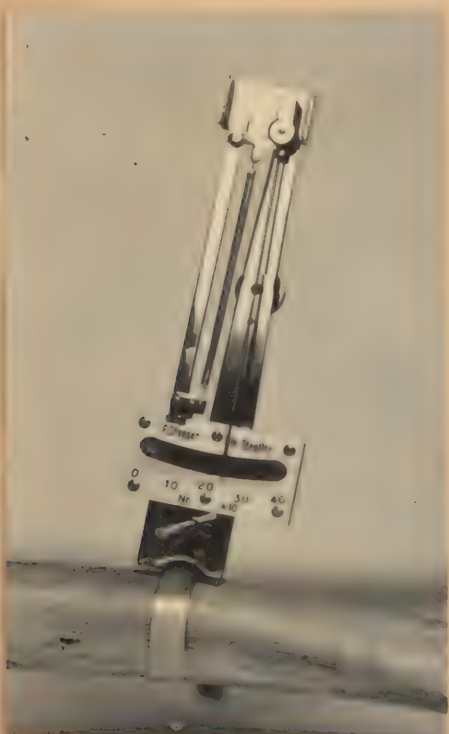


Illustration 6.
Extension meter attached to the thigh bone in order to measure the amount of extension with the bone under strain.

The bone was subjected to strain in such a way that pressure was applied on the neck of the femur by means of an upholstered pad the shape of a hemisphere so that the pressure was distributed equally upon the entire head. The applied pressure resulted from a

lever with an attached scale which made it possible to increase the pressure by adding weights. The upholstered pad was 10 cm. distant from the turning point of the lever. The weights could be moved on the lever so that either by moving or increasing the weights the pressure upon the neck of the femur varied considerably. The lower third of the thigh bone was embedded in plaster in a can made of sheet metal so that it was firmly attached. The position of the femur in relation to the direction of the exerted pressure corresponded to about the normal conditions prevailing in the standing leg. After all the exact position of the bone is not so important because the author was in a position to prove that the flow of the force in the femur within the physiological limits is independent of the inclination from the vertical axis. With this arrangement it was possible to determine the extent of deformation in the thigh bone of an adult man which is caused by strain on the neck of the femur. The deformations developing medially and laterally in the direction of the bone axis were transferred to the contours of the bone in Illustration 7 and the magnification amounts to 1:8000. The shortenings are demonstrated in black color and the extensions are cross-hatched. The figures contained therein indicate the deformations in 1/1000 mm, the shortenings appear with a -(minus) mark and the extensions with a + (plus) mark. The measured length amounts to 10 mm. The tensions correspond to the relief indicating the distribution of traction in so much as the shortenings were caused by pressure tension and the extensions by traction-tension. Consequently this relief exclusively demonstrates the actual tensions which really develop in the thigh. An illustration of that kind can never be obtained by calculation as has already been mentioned above. Furthermore it confirms the results obtained by the traction crack method which indicates the location of the traction and pressure maxima. Exactly at those spots where the first cracks appear in the varnish which result from a slowly increased strain, extreme deformations are obtained by measuring. It is specially interesting to note that once again we have to deal with two traction tension peaks. Furthermore this illustration clearly confirms the well known fact that in the neck of the femur the tensions are strongly crowded together.

In order to determine the dependence of the extent of deformation from the amount of strain the bone is subjected to, we have made a series of expansion tests with varying weights acting on the bone. The results of these tests are demonstrated in Table 1 for the three highest tension maxima.

TABLE I.

	Strain in Kilograms			
	100	200	400	800
Pressure tension maximum	2.7	5.5	11.0	22.0
First traction tension maximum	3.0	6.5	13.0	26.0
Second traction tension maximum	2.0	4.1	8.1	16.2

It will be suitable to use fresh bone. Our experiences however proved that the same values are obtained when testing the bone a couple of hours later or even 2-3 days later. The progressing dehydration of the bone however, may result in a changing of the values of the colloidal condition of the bone. It is even possible to sterilize the extension meter and to apply it to living bone. In these deformation tests it is of utmost importance that the instrument is kept accurately in the direction of the pressure- or traction-tension to be measured, because due to the condition of biaxial tension the tension differs with every direction. In the vertical direction we have to deal even with the opposite tension. The direction of the tensions from every point is easily recognizable in the scheme demonstrated in Illustration 4, because they were found out by the traction crack method.

On the one hand these tests proved that the deformations are extremely slight so that we must not be surprised that previously it was not possible to measure them. On the other hand these tests proved that - at least in connection with the tested field -the results obtained by HALLERMANN in connection with the elasticity of the bone are entirely correct, i.e. they proved that the elasticity of the bone is perfect. The deformation of the bone is directly proportional to the strain to which the bone is subjected. The objections against HALLERMANN's test arrangement were eliminated in this way. In order to eliminate additional forces he excised 100 mm long parts of the bone substance which were of complicated shape. It is obvious that the mechanical capacity of the bone may be changed, first of all because the homogenity of the bone may be disturbed because all the osteons of the bone are in direct correlation. The bone is a mechanical unit only by this correlation (compare: BENNINGHOFF, PETERSEN, KUENTSCHER).

It is most suitable for determining the additionally occurring forces to demonstrate their type, position, direction and magnitude. Their type, position and direction may be found out by means of the extension line method, and their magnitude by means of the extension meter. If the deformations in any direction arising at any point of the body can be measured it will also be possible to measure the kind and the direction of the forces acting at those points. The procedure required for this purpose is very tedious if we have only a small number of points and only a couple of principal directions of the forces. In this way however, it is possible to get a confirmation of the results obtained by the tension-line procedure.

According to HOOK's law deformations and forces must be proportional and consequently it should be easily possible to find out the corresponding forces by means of the figures given in Table I or to read them from the results of tension tests.

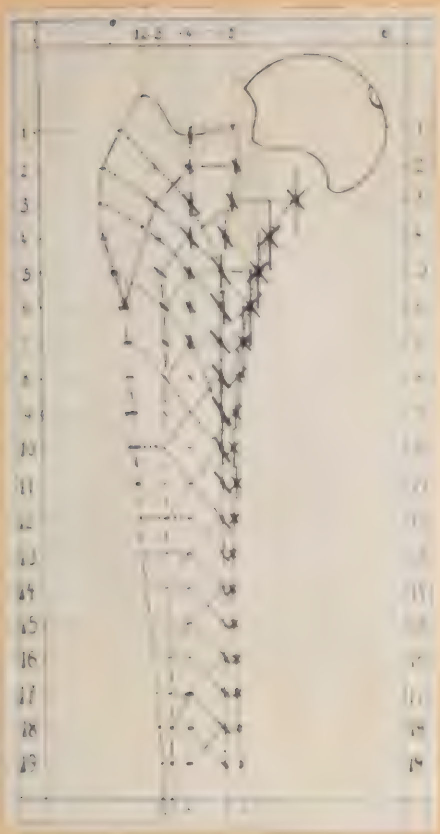


Illustration 7.
Deformations developing in the medial and lateral longitudinal fibers of the femur with a burden of 100 kilograms applied to the femur head, the scale being 1:20000 transferred vertically to the surface. The shortenings (pressure) appear black, the extensions (traction) grey.

In this connection it must be taken into consideration however, that even during one-axial tension in every case we also have to deal with a transverse deformation, which always is opposed to the main tension. A rod being exposed to tension caused by traction in the direction of its longitudinal axis becomes longer but at the same time it becomes thinner. This decrease of the diameter is not only caused by pressure forces, but it also is the manifestation of the transverse contraction caused by traction. This relation between the main tension and the transverse tension, i.e. the transverse thinning depends only on the material and must be considered to be a constant value, the so-called POISSON's constant which amounts to 10/3 in steel.

In our bone tests with the extension meter POISSON's constant value amounted to 10/2 on an average. A one-axial condition of tension exists only in those cases in which both main tensions standing vertically to each other show counteracting values with their quotient corresponding to that constant value. In all the other cases we have to deal with a bi-axial condition.

In order to find out which tensions correspond to the observed lines of force, comparable measurings are necessary with such bodies as were cut out of the bone substance and the diameter of which may easily be calculated. In this case, however, the principle of the homogeneity of the bone is disregarded. Moreover the test bodies cannot be modeled in such a way that additional forces may be excluded with certainty. This applies particularly to the measurings of the bending. Therefore the values obtained by these comparable measurements are only approximate values. As to

the alterations of length of the 10 mm distance of measurement caused by traction or pressure forces we obtained values of 0.35 - 0.5 kg/sqmm so that for the figures contained in Table I these values must be inserted in order to calculate the prevailing tension at each spot. This calculation corresponds to the values obtained by MESSERER in 1876 during his classical tests of the stability of the femur. He had observed that a femur breaks under the influence of forces causing a pressure of 1200 kilograms, and that in this case the fracture occurs at the neck of the femur. Table I shows an expansion by 6.5 thousandths of a millimeter if the strain on the bone amounts to 200 kilograms. This corresponds to a tension of 2.3 kg/sqmm. (6.5 x 0.35). In case of a strain of 1200 kg (6 x 200) the tension must be multiplied by 6 and equals 13.8 kg/sqmm. with the assumption of a straight lined extension curve. The values for resistance to tension published so far amount to 12/14 kg/sqmm for normal bone. Similar values are valid for the pressure tension. This accord is perfect because we must presume that this kind of fracture occurs at the neck of the femur as a fissured fracture. We know from experience that the stability is considerably decreased as soon as additional forces develop.

HALLERMANN observed that in correspondingly shaped testpieces the stability is only 4 kg/sqmm. The table and the graph however prove that the values at the highest tension maximum correspond to POISSON's constant and are characterized at the tension maxima by opposite (mathematical) signs. Hence it results that a one-axial tension prevails for which the normal values of stability must be applied. This favorable condition seems to be due to the suitable shape of the bone. It is well known that the elasticity of the bone decreases with advancing age. This means that under the same strain the deformation of juvenile bone is many times greater than in adult bone. The figures mentioned above may therefore be applied only to individual cases. The most important thing here is that we are in a position to measure the deformations of the bone generally developing under normal strain. Therefore we must not forget that the framework of the body, i.e. the bones, is not composed of absolutely inflexible structures.

These deformations of the bone occur while the muscles are in action and they disappear as soon as this strain ceases to act upon the bone. In case of a rhythmic muscle action the bone will be deformed rhythmically. This means that a constantly repeated expansion occurs at the traction tension maxima; at the same time a rhythmical shortening appears vertical to the longitudinal axis and vice versa this also applies to the pressure tension maxima. The bone substance is "pulsating" so to speak.

This elastic deformation of the bone during its subjection to strain must be strictly differentiated from all the other alterations of the bone, as for instance: 1: Growth of the bone in the longitudinal and transverse direction in juvenile age. 2: In 1885 POMMER was in a position to prove that the bone is constantly subjected

to constructive and destructive alterations according to the strain the bone is subjected to. 3: Changes of the shape of the bone may be caused by some disease processes, by disturbances of growth, i.e. by processes which we call epiphyseal necrosis, by the developing of ulcers, by special diseases (as for instance lues) or other inflammatory processes.

Two symptoms are characteristic for these deformations. They occur slowly, in a couple of weeks or months and not in a fraction of a second as in elastic deformations. Moreover these deformations (local increase or decrease of volume) occur always only once. The previous structure will never be fully regained as in elastic deformations.

B. Diseases of the Bones and of the Joints caused by mechanical Conditions.

Pathological Fracture and Reconstruction Zone.

If there really are diseases of the bone which are due to mechanical over-strain and in which the mechanical factors are decisive for the originating of the disease, in such a case the tension maxima must correspond to the localization as to the location or course of the disease. All this could be proved by the author in a series of such diseases.

First of all we have to deal with the so-called zones of reconstruction. LOOSER was first to recognize the developing of those zones and he described them in detail. Therefore they are also called LOOSER's zones of reconstruction. From the clinical point of view these zones show hardly any symptoms. There does not exist any dislocation, very rarely we sometimes observed only a slight angulation. By thorough examination it will be possible to diagnose only a slight marked local sensitivity against pressure. Sometimes also a slight springing flexibility may be diagnosed. In such a case the patient complains about slight pains or discomfort during the examination. In no case however, will it be possible to find any symptom characteristic for a fracture; as for instance abnormal motility, crepitation or diminished function.

Consequently the zones of reconstruction are observed only in the X-ray, where they appear distinctly. In special cases the impression prevails that a separation of continuity of the bone had taken place. Lines of absorption run obliquely and transversely through the bone, which are several millimeters - up to 8 mm. - in size. In these lines the structure of the bone is markedly absorbed or it may even disappear completely. In such a case one may have the impression as if the bone substance had completely disappeared. According to KOEHLER spots of that kind look "as if they were erased". Only in rare cases are several clarification foci observed. Sometimes periosteal clarifications prove that the periosteum is damaged. The zones of reconstruction never show toothed margins which are characteristic for fractures but their

margins are always smooth.

Histologically LOOSER found a process of reconstruction of the bone. The old bone lamellae are destroyed by lacunary resorption and in the first phase they are replaced by some calcium-free bone which appears as a plexus. These zones of reconstruction grow in those parts of the bone which are weakened because of a general damage. They are often observed in cases of rachitis, late rachitis and osteomalacia. FROMME has observed them also during the war in cases of diseases due to hunger. LOOSER blames mechanical conditions for the developing of those zones but he does not give any definition for them. He considers these zones of reconstruction to be "pathological formations of callus" at "mechanically irritated spots" of progressive bendings and fissures and infractions of the bone which arise periodically. He classifies them as infractions. The clarifications are considered to be of traumatic origin because they have the characteristic shape of transverse or oblique cracks and clefts and because they are usually observed as spots of marked bendings or angulations which however may occur even after the development of the clarifications. Sometimes they were also observed at spots of previous incomplete fractures in the bone. According to LOOSER however they are not fractures regarding their clinical and roentgenological symptoms. Moreover LOOSER speaks of a "chronic traumatic irritation" which causes the disappearance of the old lamellar bone by lacunary resorption. Furthermore he observed that in the fibrous marrow which regularly develops at such angulations plexus bone is formed. The disappearance is explained by the general experience that lamellar bone is particularly sensitive to "chronic mechanical irritations".

There is a process analogous to that of the resorption of the bone due to the pressure of an aortic aneurysm or of a tumor or the reduction of the root of a tooth by the pressure of the remaining teeth.

MARTIN was first to observe in tests on dogs that zones of reconstruction may develop also in normal bone substance. In order to study the question of the development of pseudarthrosis he sawed through the radius of the test animals. In all cases characteristic changes were observed in the ulna at a site opposite to the sawcut, sometimes these changes were also observed somewhat more distally, they start at the exterior and progress in the direction of the center of the bone. All this results in the formation of a reconstruction zone of the entire bone. About a fortnight later the X-ray contours of the ulna became indistinct at a well definable place. Due to a periosteal accumulation of bone tissue the ulna becomes thicker assuming the shape of a spindle and thus the characteristic structure is lost. 60 days later the callus is cloudy and 70 days later at the spot opposite the sawcut a cleft may be observed which gradually widens and deepens. 75 days later only a small bony bridge is left and after a lapse of 96 days a cleft separates the bone.

The development of this alteration of the ulna opposite the sawcut of the radius was explained by BIER and MARTIN by biological and chemical "noxae" which have their origin in the sawed bone and which cause a sympathetic" atrophy in the adjoining healthy bone. The adjacent bone becomes "infected by the formation of callus.

W. MUELLER was able to confirm MARTIN's findings, but his explanation was quite different. He concluded that the increased mechanical strain was the cause for the alteration of the bone. The bone not sawed through is subjected to a greater strain through the disability of the other bone and it reacts with the formation of a reconstruction zone. W. MUELLER came to this conclusion because these changes are observed only in the considerably weaker ulna when the radius is cut through. When cutting through the ulna no changes are observed in the radius which bears most of the weight anyhow and by sawing through the ulna the strain on it is not considerably increased.

W. MUELLER observed that in juvenile bone changes of this kind occur only in the zone of growth and not at the opposite area. In this way he has confirmed the clinical observations which prove that the zones of growth are particularly sensitive to mechanical strain.

Furthermore W. MUELLER was in a position to prove that these changes correspond to those described by LOOSER as zones of reconstruction. He found the same roentgenological and histological symptoms.

It is a matter of fact that W. MUELLER places in the foreground the mechanical conditions of this problem. Nevertheless he does not refer in detail to the kind of strain. He simply speaks of "mechanical strain" without dealing in detail with the actual forces as to kind, direction and spots of impact. Only when dealing with the strain on the epiphyseal line does he speak of "abnormal strain caused by pressure" and also of "lateral forces causing traction".

WALTER gives us a more clear definition of the forces which cause the formation of LOOSER's zones of reconstruction. He is of the opinion that they develop "by a constantly repeated strain acting in one direction which is not identical with the direction of the traction and pressure, but which has a bending effect upon the bone. Thus, the bone cannot compensate the additional strain by hypertrophy either because of the rapid succession of small mechanical impulses or because of their accumulation".

In this connection I would like to say that an analysis of any "bending strain" is quite possible. Any bending takes effect as traction strains of the marginal fiber on the convexity and as pressure strain at the concavity.

LEXER and SEELIGER agree with W. MUELLER's view that this was caused by purely mechanical factors. "LEXER's clinic cannot become reconciled to the theory of a sympathetic bone atrophy and as long as it is not possible to explain the existence of the "noxae" or other mysterious forces developing in the neighboring bones, that long will it not be possible to abandon our theory." The forces ob-

served in MARTIN's test were dealt with in detail by LEXER. In tests on dogs he examined the influence of strain by means of X-rays and found out that in case of a dangling foreleg the radius is located precisely in front of the ulna. As soon as the bone is subjected to weight bearing a pronation is observed. If the radius is defective the distal radius fragment causes a pressure on the normally somewhat convex shaped ulna and this causes its bending in the backward direction.

LEXER is of the opinion that besides the pressure of the radius we have also to deal with forces causing traction which are due to the pronation. He points out that pseudo-fractures occurring in bone which was transplanted for bridging over fracture clefts often refer to the same process of reconstruction.

The author has tested the observed tension maxima by means of the traction crack method and came to the following observation:

In fresh dog fore-legs, the radius and ulna were exposed and the joints and ligaments were kept intact. After that the radius was cut through at several spots and the bones were covered by the varnish described before. The flow of force was demonstrated by pressing the preparation together in analogy to an approximation of the elbow and the wrist. In this way it was possible to prove that traction tension maxima existed on the ulna at the spots corresponding to the places where the radius had been cut through; these were found on the averted side of the ulna. MARTIN's illustrations show clearly - and MUELLER had pointed thereto - that the zones of reconstruction develop at that side which is turned away from the radius. A pressure of the radius fragment upon the ulna was not exerted during the experiments - as was supposed by LEXER- because a pressure of the musculature was completely eliminated. It may be possible that this pressure is of some importance in vivo but it is negligible in comparison to the pressure of the muscle action which causes the development of the zone of reconstruction.

How may one explain the development of a tension maximum on the ulna opposite the sawcut? When cutting through the ulna instead of the radius we also observe tension maxima in the place opposite the saw cut. When comparing the foreleg bones of the dog with the forearm bones in humans we observe that the dog bones are not so freely movable one against the other. They are located closely together and are mechanically strongly united by the ligament interosseum and the joint ligaments so that they act as a unit. The sawcut acts like a notch cut into this bone. At the base of such a notch one will always find tension maxima because here the lines of force flow together. With reference to a practical example one will cut a notch into a stick so that upon bending it will break at that very spot in consequence of the development of a traction tension maximum. (Illustration 8).

Illustration 8.

Diagram of the effect of the notch. Pressing together of the lines of force as in a stick after a notch had been made in the stick. If the notch is not cut through the tension peak will be located at the lower third of the ulna. By cutting through the bone however, the tension peak is shifted to the vicinity of the sawcut. The mechanical union is not absolutely stable so that the tension peak is sometimes not shifted to the corresponding location of the sawcut.

The above described "effect of the notch" is very important in connection with the explanation of many such "mechanically caused pathologic conditions of the bone". A minor infraction of a bone means that the tension maximum is shifted to that spot. After cutting through the ulna the tension maxima which develop on the radius will not cause the development of a reconstruction zone because the tensions in that strong a bone cannot become strong enough to surpass the dangerous limit.

Thus in the human ulna which is relatively strong the development of zones of reconstruction are not frequently observed after radius fractures. Due to the fact that both bones are only loosely united it certainly would not correspond to the affected place. In a fracture without sufficient quantities of callus or in those cases in which the callus is not yet mechanically strong similar reactions are to be observed. In such a case the tension maximum normally located in the neck of the femur will develop in the fracture cleft. This may explain the above mentioned development of zones of reconstruction in healed-in bone grafts. This problem will be dealt with in detail after we have studied the influence of the flow of force upon the healing of a fracture. The author was in a position to prove that in all cases LOOSER's zone of reconstruction always correspond to the location and the course of the tension maxima. Such a zone of reconstruction corresponding to the neck of the femur tension-peak is demonstrated in illustration 9, which shows the neck of the femur in a 23 year old patient who suffered late rickets.

A similar zone of reconstruction is also observed in children, which, according to WALTER must be blamed for the coxa-vara congenita of small children. Many reasons have been held responsible for the development of this condition, for instance congenital alterations, endocrine factors, etc. The zone of reconstruction develops in the neck of the femur; it starts above and runs through the neck vertical to its axis. In this way a triangle is formed between the zone of reconstruction and the epiphyseal line. It coincides exactly with the location and course of the first traction-tension maximum. Best proof

for the mechanically conditioned cause is - according to WALTHER - the fact that healing is achieved after a subtrochanteric osteotomy. In this way the flow of forces is fundamentally changed. This will be shown later.

Illustration 9.

Zone of reconstruction in the neck of the femur of a 23 year old patient suffering from late rickets. The zone of reconstruction corresponds to the tension maximum but it is dislocated due to the peculiarly long shaped neck of the femur and its coxa-vara position. There was a discomfort caused by the zone of reconstruction. Healing was achieved after a subtrochanteric osteotomy.

To the field of the mechanically caused disease belong first of all the so-called fatigue fractures which were so frequently observed in Germany shortly before the outbreak of the second World War and which were due to the hastily carried out training of soldiers and men for the German Labor Service. Entirely new localizations of these diseases were observed which previously were not known.

Fatigue-fractures are observed in the army only in those recruits whose bones had not yet become accustomed to the increased strain they are subjected to. This means that their bones were not given time enough to build sufficient quantities of additional bone by the stimulating effect of the function and to become in this way mechanically stronger. This increase of the bone appears as some kind of a deformation which proceeds very slowly and which takes many weeks and months. In general only people with long and thin bones are afflicted with this disease whose elastic deformations are much stronger than those seen in others. In this example a fracture may occur by an increased strain without any alteration of the bone. Vice versa, in case of an unchanged strain but by a decrease of the mechanical stability of the bone this fracture mechanism may develop and a tumor will act in much the same way as the notch cut into the stick as referred to above. Sometimes only minor changes of the surface will suffice to cause a fatigue fracture which acts like a notch as described by HAASE. On the other hand the bone tissue itself may become mechanically less strong because of gradual changes in the bone somewhat in the way of a bone disease. It is also possible that in the beginning of the functional process of reconstruction of the bone such a degeneration of the substance may occur if the over-strain lasts too long. Such a damaging effect may also be caused by strong X-ray exposure. Consequently the fractures of the neck of the femur in women who had been treated by X-rays because of cancer of the uterus, referred to by PHILIPP and BAENSCH, must also be considered to be fatigue-frac-

tures. This strong roentgenization represents an unintentional creation of circumstances which produce fatigue fractures, i.e. in the human being itself, which in a series of cases was unsuccessful. In fact the neck of the femur is markedly exposed to the roentgenization. The previous history of these fractures proves that in no case did a trauma occur and these fractures look just like fatigue fractures, as those observed at the same site, f.i. in recruits.

This kind of fracture which has been known for a long time and which was described in detail by DEUTSCHLAENDER is the so-called "Marschfraktur" (fracture caused by marching) of the metatarsals I and II. Here we observe a transverse fracture of the bone in most of the cases without any dislocation. In many cases the only symptoms to be observed are either an infraction or a very fine fissure. Also in these cases the author was in a position to prove by means of the traction crack method that the fracture planes correspond to the tension maxima. The situation was similar in the cases of fatigue fractures which were described later. Only certain bones are afflicted with this disease and each of them in quite a characteristic way. In the tibia we observe a cleft running transverse to the longitudinal axis. In general this cleft is located about a hand's breadth below the cleft of the knee joint, in some cases somewhat lower. In the fibula we also have to deal with transverse fractures located at varying heights. Fractures of this kind are most frequently observed in artillery men, but they occurred only with certain exercises. In thigh fractures the damages caused by overstrain occur in the form of fractures of the neck of the femur the fracture planes of which run almost vertically.

Illustration 10.

Fatigue fracture of the neck of the femur in a 21 year old man at the first traction-tension maximum.

Illustration 10 shows the picture of a 21 year old worker in the German Labor Service who after heavy work in the moor, to which he was not accustomed, suddenly and without any related trauma, complained about increasing pains in the hip and after that showed all clinical symptoms of a fracture of the neck of the femur.

Injuries of this kind were also observed in the pelvis and were described as transverse fractures of the pubic bone and ischium (according to MALGAEGNE's publications). Transverse fractures of the spinal processes of the dorsal vertebra were observed in men who had engaged in strenuous shoveling. All authors agree that the fatigue fractures are iden-

tical with the above mentioned LOOSER's zone of reconstruction.

The author is of the opinion that in this case we have to deal with two quite different problems: The fatigue fracture is due to a special fracture mechanism which can be simulated in dead bone or even in metal. The reconstruction zone however represents a biological reaction of the bone which can be produced only by living tissue.

This does not mean that transitions between the two are not possible; on the contrary, they were frequently observed. In the literature his theory has frequently been discounted despite the fact that the author was in a position to prove this theory. Therefore at this place reference should be made to it because these processes seem to be important in connection with the healing of fractures.

Attempts to produce fatigue fractures.

In a series of experiments preparations of human bone were subjected to intense rhythmic strain. It was attempted to produce the same strain on the bone which living bone is subjected to and which finally results in a fatigue fracture. The bones were held by a special apparatus which made it possible to exert a rhythmic strain which caused the destruction of the bone by angulation. This strain was produced by an eccentric gear driven by an electric motor of 15 HP. The movements of the bones were transferred to kymograph tracing. The pointer was attached to that end of the bone which was not fixed and in this way it was possible to record the extent of the compression of the entire bone which occurred as soon as the bone was subjected to strain. Consequently the extent of the vibration was at the same time a measure for the force applied. Measurements were made to find out the extent of the shortening under various strains. For this purpose the condyles of the thigh bone and the head were filled in with WOOD's metal and after that the joint ends were approached to each other under increasing pressure. The motor we used has a frequency of revolution of 1500/min. The force the femur was subjected to was set at 100 kilograms. It is a matter of course that this power is too little to produce a lasting change if the bone is subjected to that strain only once, for MESSERER's classical tests proved that the bone breaks only when it is subjected to a strain of 700 - 1000 kilograms in this way. Even after the bone had been subjected to strain for a period of one minute, - which corresponded to 1500 applications - the bone did not show any symptoms. After the bone had been subjected to strain 35,000 - 40,000 times we always observed a fracture cleft on the surface of the neck of the femur at that spot which corresponded to the traction-tension maximum. This is in conformity with observations made in fatigue fractures of metal. Here also the fatigue fracture develops as a beginning fracture ("Anbruch") or preferably a beginning fissure ("Anriss") which progresses slowly. Furthermore these find-

ings correspond to the histological observations of SCHUERMANN of injuries of the bone caused by overstrain; SCHUERMANN, however, observed most frequently fractures of the córticalis only. Within a period of ½ - ¼ minute the fracture progresses in the vertical direction corresponding to the traction tension maximum. To achieve this result the bone had to be subjected to the strain of 350 - 750 additional vibrations which means that the process of breaking progresses rather quickly. After that the neck breaks off completely and we see a bone which shows the same clinical picture as fatigue fracture bones as to exterior, position and course. The fracture plane is relatively even but not absolutely smooth. Illustration 11 shows 2 fractures produced in this way.

The somewhat irregular course of the fatigue fracture in the bone corresponds to the clinical picture. It can be recognized in many X-rays. Contrary to the findings in bones, metal fatigue fractures are absolutely smooth and of a peculiar velvet-like gloss. This smoothness is produced by the fact that the microscopically small crystals of the metal structure grind each other off during the gradual progress of the fracture. This does not apply to the bone, presumably because of the fact that, especially in the spongiosa, no corresponding particles are opposed to each other and because of the fiber structure. Also in other non-metallic bodies this smooth polishing of the fracture planes is not found. Nevertheless a fatigue fracture of wood is relatively more smooth than a fracture caused by static or dynamic forces. Fatigue fractures of the bone produced in these tests occurred under the influence of forces which were much smaller than those observed clinically in injuries caused by overstrain. There is no doubt that, for instance, during a training march of 30 kilometers the single thigh bone is subjected to a strain stronger than 100 kilograms. The pack to be carried by the soldier amounting to about 30 kilograms is increased by his own body weight of about 70 kilograms and this weight exerts its pressure upon the femur with each step. The most important thing, however, is the strain on the muscle diameter which attains much higher values. These values cannot be calculated. On the other hand however, we must take into consideration that with an increased frequency of strain the resistance against fatigue fractures is considerably decreased. As to the order of magnitude the weights used during the experiment might approximate the weights occurring under normal physiological conditions. The most substantial result of our experiments is the proof that it is possible to produce fatigue fractures by rhythmic strain on a bone which in every respect are similar to those observed clinically. The same was accomplished not only in the femur, but also in the pelvic bone, tibia and the metatarsal bones, in an absolutely typical way. The above mentioned transverse fractures correspond to the clinical cases of transverse fractures due to fatigue. In all cases there was only one single fracture cleft and in no case were small bone particles found in addition to the

two fragments.

a) X-Ray   b) Photographs

Illustration 11.

Fatigue fracture of the femur, caused by rhythmic strain with a motor. 100 kilograms single strain were applied 40,000 times.

The occurrence of fatigue fractures in vivo is also frequently observed after the bone has been subjected to a determinable constant repetition of strains. MEISEZAHL observed that in a marching unit fatigue fractures occurred simultaneously in quite a number of soldiers, after they had marched about 20 kilometers.

It seems strange to observe an absolutely transverse fracture developing while the bone is subjected to a rhythmic pressure strain in the direction of its longitudinal axis. In the tibia the fracture is located about a hand's breadth below the knee joint cavity. The tension maxima however, is very flat and extends to a large area on the surface of the tibia so that the fracture site may be located considerably farther distally. In one case it was possible to produce such a fracture plane in the lower third, which of course ran in the transverse direction.

The X-ray taken from fractures produced by motor power correspond to the clinically observed picture of fatigue fractures as to direction, shape and location of the fracture cleft.

The question arises: Why did a zone of reconstruction and no fatigue fracture develop in MARTIN-MUELLER's tests? The test animals subject the operated limb to weight of course, but only cautiously; at any rate they nurse the injured limb. In some cases an additional immobilizing starch cast was applied during the first few days after the operation. The stress on the limb was strong enough so that the ulna is strained excessively because the radius has been resected and consequently a zone of reconstruction develops.

The author was in a position to prove that in those cases in which the test animals were forced to subject the operated limb to more strain, fatigue fractures developed. In order to prove this both fore-legs of the test animals were treated in the above described way. Thus the test dogs had to subject the damaged limbs to more strain. Zones of reconstruction did not develop but fractures occurred 6 - 9 days later. These fractures look like fatigue fractures with smooth transverse fracture clefts. Dynamic causes could be excluded practically.

Further tests were made in order to study the mechanism of these fatigue fractures and to exclude all other side effects. In this way we came to new arrangements which seem to be useful also for other tests concerning the effect of mechanical over-strain, such as: development of injuries of the joints or changes of the connective tissue. The first condition also in these cases is to force the test animal to subject the limb to very strong mechanical strain, which of course is counteracted by the psyche of the animal but which was excluded by "somnifen" permanent narcosis. For this purpose a vein was exposed and we inserted a cannula which made it possible to inject the contents of one or more ampoules at intervals of about 5-8 hours according to the size of the dog. In order to avoid an obstruction of the cannula by coagulated blood after each injection a mandrin was inserted. In this way it is possible to bring the limb tested into action either by cerebral or peripheral stimulation. In the tests described here the skin was cut by an incision of about 3-5 cms. length at the lateral edge of the axilla using dogs of different age and size. The plexus brachialis was bluntly exposed from there, clamped and severed proximally to the clamps. The clamp was insulated from the surrounding tissue and skin by a rubber tube. After that the electrode of an electric battery was attached to the clamp. A wire was wound around the paw of the test animal and after that it was sealed in plaster. This plaster-cast was fastened to the table on which the animal lay by means of a screw-clamp and the wire was connected with the other electrode of the battery. In most of the cases we used ERB's "TONISATOR", in some cases a "PANTOSTAT". In this way it was possible to stimulate the plexus at any interval and thus all muscles of the limb were brought to action. In general the stimulus was faradic; the device was set for maximal stimulation. Due to the fact that the entire muscle diameter was in action at the same time and the paw of the test animal was attached to the table only minimal movements of the joints were possible. Almost the entire

muscle strength was used to achieve the above described deformation of the bone. This deformation is only slight in comparison to the movements of the joints so that the way along which the muscles act is very short and the muscle work is not strong. This may explain why the test may be continued for several hours without a noticeable fatigue of the muscles developing. After a lapse of 20-36 hours the tests were stopped without any noteworthy decrease of the efficiency of the muscles at the end of the test period. With such an arrangement it is quite possible to subject living bone to strain for a very long period of time under any rhythm with the blood circulation undamaged. The main work of the muscles is reserved for the strain on the bone. In all dogs the radius of the fore-leg was resected for about $1\frac{1}{2}$ - 2 cm. and the leg stimulated in the above described way. Even with strongest faradic or galvanic stimulation of the nerves it was not possible to break the ulna with one single electric impulse. The number of the rhythmic electric impulses varied during the different tests and lasted for 3 - 10/sec. With the maximal stimulation which was administered in all tests the muscle action was extremely strong, which was readily noticeable either by touching the test animal or by introducing the finger into the resection site. In the latter case a rhythmic compression of the finger could be perceived. The strength of the muscle work was constant and did not let one recognize any decrease. It varied however in the different test animals. It was not possible to determine accurately the reason for this variation. In each case however, the ulna broke after a period of 16-21 hours. These fractures look just like the ones described above (first tests). In all cases they were located opposite the resection site and in all cases we had to deal with transverse fractures, which were slightly jagged. There is no doubt that we were dealing with fatigue fractures. These tests therefore prove the fact that also in our first tests fatigue fractures were obtained.

In no case was a change of the arm above the elbow observed despite the fact that the strain on the arm above the elbow was considerable. Maybe the single strains on the arm above the elbow were within the normal limits, but we cannot prove that. There is only a small percentage of human beings who suffer a fatigue fracture during the experiment of a training march. Therefore thousands of dog tests would be necessary to give a definite opinion. For the time being the only possibility to produce a fatigue fracture is to weaken the bone mechanically by very strong stimulation of the entire musculature and by cutting a notch into the bone which practically is the equivalent of resection of the radius.

Finally I would like to refer to a fact which proves that here we have fatigue fractures. In all dogs of the last test series the sound fore-leg was removed after the test and a more extensive resection of the radius was made than that in the first leg. When trying to bend the ulna in much the same way as it had been done before by the muscle traction effect, it was in no case possible to produce a fracture even by jerks. The ulna could be bent

to such an extent that the two resection planes touched each other as is demonstrated in Illustration 12 a.

A fracture can be produced only by a many-thousand-fold repetition of the bending-through process of the bone until finally the structure of the bone tissue becomes incoherent. Such a fracture is a fatigue fracture (Ill. 12b).

The following conclusion must be drawn from the above described tests: In case of a sudden over-straining of a bone, an effect that may be produced in the ulna of the dog for instance by the resection of the radius, a fatigue fracture will occur after a few days at the site exposed to the heaviest strain. The fact that the fatigue fracture does not occur immediately on the first day if both legs are resected probably must be ascribed to the circumstance that the animal nurses the injured limbs after the operation. The fatigue fracture in this case will probably occur in the sound or nearly sound bone. In any case it was not possible to prove any roentgenological alterations. Neither is there any occasion to assume that within a period of 6 days - as observed for instance in the first test - the reduction of the bone substance will become so marked that the mechanical capacities of the bone tissue must be considered to have considerably deteriorated. Of course one must assume that the process of disintegration of the bone commences which then becomes apparent after 5-7 weeks as is clearly demonstrated by the tests of MARTIN and MUELLER. But no greater mechanical significance should be attributed to the phenomenon in the beginning. There is no such possibility in the tests of the second series in which fatigue fractures were produced in living dogs by the electric excitation of the nerves. It is not permissible to assume that such a structure alteration of the bone becomes manifest within the first 16 - 21 hours. Nevertheless these fractures look exactly like those of the first series of

a) Angulation but no fracture

b) Fatigue Fracture.

Illustration 12.

Fatigue fracture of the ulna in a dog produced by a continuous rhythmic stimulation of the plexus after the resection of the radius. After an extended resection of the radius the ulna may be bent so much that the resection planes touch each other without a fracture appearing.

fractures. The results of the tests confirm the thesis, that fatigue fractures are genuine fractures produced by an exactly definable mechanism, i.e. by a constant repetition of the same strain. In this case living bone is fractured in exactly the same way as dead bone. Due to this mechanism sound, diseased, or other bone tissue, which had undergone structural changes may break. Generally speaking a fatigue fracture will occur only when a certain critical value is exceeded. This is one of the specific characteristics of the fatigue fracture. In addition, the single strain on the bone must in each case exceed a certain critical minimum. If the critical minimum value is not attained, the bone will not be fractured. The tissue will stand the strain it is subjected to and even its frequent repetition. This may explain why in MARTIN and MUELLER's tests no fracture was observed. The strain which is exerted upon the ulna is not so heavy as to attain the critical minimum value. It is however, above the normal value so that a zone of reconstruction will develop at a later time.

A sound and also a diseased bone will react by a fatigue fracture if subjected to a rhythmic over-strain. If the single strain does not exceed a certain critical minimum value, a zone of reconstruction may develop. This zone of reconstruction will however develop only in diseased bone or sound bone which, under the influence of the constant strain, has undergone gradual changes. This over-strain is in all cases the result of muscle traction either by especially powerful and frequent muscular actions occurring (as for instance in case of a march fracture), or the bone is weakened. In this case the bone may be weakened through mechanical forces in the sense of the "notch" effect. A traumatic infraction may also be considered as such a notch infraction or the bone is debilitated because the mechanical capacities of the tissue are diminished as for instance by the effect of X-rays or a disease such as tabes.

The most impressive method of producing fatigue fractures by experiment is the application of X-rays. The above mentioned observations by PHILIPP and BAENSCH as to the development of fractures of the femur neck after an intense irradiation of the uterus led this author to the idea of producing fractures of that kind in dogs. The extended research work started in collaboration with the X-ray expert H. BADE, whose early death is regretted, did not show any success. The results of these investigations are given below.

Opinions differ on the effect of X-rays upon the bone. Therefore it seems to be worthwhile to describe these tests and their results. We shall only discuss the effect of the X-rays upon the bone as the framework of the body, while their effect upon the bone marrow as a hematopoietic system is not investigated.

The first report on a disorder of the growth of the skeleton came from PERTHES as long ago as 1903. He had irradiated one wing of a chicken, one day after hatching, with a dose of 12 German unit skin doses (German abbr.= HED) and observed in the sequel a distinct retardation of

growth of the irradiated side of the chicken.

The observations of PERTHES do not seem to become general knowledge, for in 1907, during the Third Congress of the German Roentgen-Society the information given by FOERSTERLING as to the disorders of growth caused by X-rays was received with great consternation as something quite new. FOERSTERLING had reported on the retardation of the growth of young rabbits exposed to total irradiation with relatively small doses. But, even in cases of partial irradiation he was able to observe distinct inhibitions of growth, the extent of the damage being in proportion to the dose administered. Furthermore he observed that the effect was the stronger, the younger the animal was. Consequently he concluded that in small children one must in every case be very careful with the use of X-rays. In the discussion which followed his report, HOLZKNECHT declined to apply FOERSTERLING's observations made in animal tests to the human body, because the test animals selected show an incomparably more rapid growth than humans. Contrary to these quite definite results obtained in animal tests, only a small number of observations on humans were available at that time. In some cases at least it was doubtful whether the damages were exclusively caused by X-rays. In order to find out whether FOERSTERLING's conclusions with regard to humans were correct a committee was established after he had finished his report which was supposed to gather and examine all material available. In the following year FOERSTERLING himself reported about the results obtained.

None of the surgeons had observed any disturbance of the growth as a consequence of diagnostic measures, in 13 cases it was stressed particularly that no disturbances of growth had occurred in children exposed to irradiations.

Only in five cases was it possible to blame X-rays or radium emanations for the development of disturbances of growth, but in all of these cases greatest caution was required as to the evaluation. After that the committee came to the conclusion that in humans the danger of a disturbance of growth is only very slight. A damaging effect on the growth was considered to be possible only in cases of very high doses administered to very small children.

As a result of the hardly ever reported damages to humans, PERTHES in 1925 came to the conclusion that the danger of disorders of growth must be only slight because otherwise a larger number of cases of this specific kind would have been reported. BIRK and SCHALL came to the same conclusion in 1926 and emphasized once more that there was no conformity between the results of the animal tests and clinical experience.

In 1928, BECK discussed six cases from the surgical clinic at Kiel who at an age between 1½ and 6 years had received high doses of X-rays for treatment some of whom showed considerable disorders of growth. Three of these cases suffered from tuberculosis of the knee joint and three of them from tuberculosis of the ankle joint so that

the question whether this was really a pure damage caused by X-rays could not be definitely answered; for it is certainly possible that the existing tuberculosis was responsible for the disturbance of growth.

Disorders of growth in man do however occur, as was shown among other things by a case published by HAENISCH. This was a young woman who as a girl of 3½ years was exposed to an intensive X-ray treatment because of a tumor of the right upper arm. She was suffering from a conspicuous disturbance of growth of the right upper arm, of the right shoulder bones and of the right side of the thorax. Moreover, there was a serious dystrophy of the right breast.

Consequently we must admit that there is a damaging effect on juvenile bone.

How about the danger of a damaging effect on human adult bone? In 1930 FLASCAMP reported, in his monograph about damages caused by X-rays, that a damaging effect on healthy adult human bone could not be observed.

As to the possibility of a damaging effect on diseased bone he was of the opinion that in those cases we are not confronted with true damages caused by X-rays but with combined injuries.

I also believe that the jaw necrosis occurring after irradiation principally as a damage of the bone hardly ever constitutes a pure X-ray damage as in most cases it is observed only with either carious teeth or in cases of infectious processes.

Likewise all known cases of serious bone damage and extensive X-ray ulcera after an obvious overdose with X-rays do not suggest a particular sensitivity of the bone.

BAENSCH's and PHILLIPP's cases of fractures of the neck of the femur in women with uterus carcinoma which were irradiated from lateral pelvic areas and which the authors traced back to the irradiations as the cause for them suggests the conclusion that also adult bones - at least to a certain degree - are sensitive to X-rays. In the cases in question we are not dealing with woman of advanced age - as suggested by ELLINGER - for one of the women patients was only 55 years old, the two others however were 68 years old. The female patient referred to by BAENSCH was at the time of the irradiation only 45 years old. In the case published by BAENSCH in which according to the dosage recorded, an overdose was applied and also in PHILIPP's three cases with fractures of the neck of the femur there is no doubt that they were caused by X-rays. In PHILIPP's two cases of the 68 year old patients the possibility must be admitted that a senile osteoporosis might have played a certain enhancing part. SCHIFFBAEUMER published a quite analogous case of a fracture of the right femur neck in a 67 year old woman who had been treated by X-rays and radium because of an inoperable acute carcinoma of the cervix.

It is my opinion that in all cases with straight fracture lines running vertical to the axis of the neck of the femur we have to deal with typical fatigue fractures because all of them are located at the same spot, i.e. at the spot of highest tension. A bone damaged by X-rays could not stand the usual minimal strain of daily life any more and reacted upon the relatively too high strain in the way of a fatigue fracture.

The inhibition in development of the growing bone due to X-raying observed first by PERTHES soon gave the incitement for experimental studies of the formation of callus. SALVETTI was the first to demonstrate with radius fractures of rabbits that after irradiation the bony healing of the fragments was delayed. In his experiments the fracture sites were X-rayed every day for a period of ten minutes. Consequently the total dosis was presumably higher as the author did not give accurate data on the doses administered.

Similar observations were made by GLUZET and DUBREUIL. Contrary to their findings ALBEE found neither a delaying nor a stimulating effect of X-rays upon the healing of the fracture. In a great number of rabbit tests FUKASE observed a favorable influence of X-rays upon the formation of callus. This author holds for a difference between the quality and the quantity of callus which to a certain degree are antagonistic to each other. According to his studies a slightly smaller amount of callus is formed when medium doses of about 400 units are administered. The X-rayed callus shows a better calcification than would be normal, and healing results faster than without irradiation. After the application of small doses of 200 units no distinct and regular improvement of the healing process was observed. In his tests in which shortly after the injury very large doses of X-rays were administered hardly any callus appeared for a period of two weeks. After that time he observed an increased formation of callus which was ascribed to a deep hyperemia as a consequence of the intensive X-raying. Bony healing is delayed.

Starting from the concept that small doses of X-rays stimulate the cellular metabolism several surgeons tried to increase the formation of callus in humans by irradiation. FRANKEL, ESSER, KOHLER and others have irradiated fractures with small doses of X-rays and they believe that they were successful in speeding up the healing process. As pointed out by Walter MUELLER in 1923, this method is of no practical significance, which proves that so far no noteworthy results were obtained. Today most X-ray experts either deny the biopositive effects of the X-rays or they at least show some scepticism as regards them. It is a matter of fact that large doses of X-rays inhibit the formation of callus. Furthermore we know that fractures in intensively X-rayed bones do not heal.

In all experimental studies made during the last years the authors unanimously have come to the conclusion that X-rays cause an inhibition but in no case a speeding up of the formation of callus and a consolidation of the fractures.

HILLAROWICZ and BROSS allegedly observed pronounced disturbances of the formation of callus even after the application of very small doses of X-rays. As a result of their observations they warn against making an excessive number of roentgenograms in fractures. This apprehension however is unfounded. Surgeons and roentgenologists agree that X-ray examinations cannot be blamed for an unsatisfactory healing of a fracture.

In my personal tests, dogs were given high doses from the lateral and medial aspects on either one or both femur necks. We did however, not succeed in producing fatigue fractures even after increasing the dosis up to 12 times 400 units per field, in which case both fields of the one side were exposed one after the other on the same day.

When an extremely high dosis was applied most serious damages of the skin and the musculature were observed so that the test dog had to be killed three months later. But even in this case of a most serious over-dosage, the X-ray showed no changes of the X-rayed bone. The doses we administered in this case were as follows: 180 kV, 4mA, filter 0.5 Cu, 1 .o Al, FHA 30 cm, intensity 37 units per minute, HOS, 1.1 mm Cu. The dose of 400 units represents the effective skin dosis, the daily dose acting upon the neck of femur amounted to 560 units. This means that both necks of femur received more than 8000 units including the additional dose from the other side. Between the irradiation series of either side there was an interval of two weeks.

If we did not succeed in producing a fracture of the neck of the femur in dogs by deliberate over-doses one must not forget that the static conditions in the neck of the femur of dogs as quadrupeds are much more favorable than in man in whom it is just the femur neck that has to stand the greatest tension because man walks in an upright position.

Furthermore it must be kept in mind that an injury of the bone through irradiation frequently may remain latent for a very long period of time - as stressed by REGAUD - and that manifestations of these injuries are observed only after a trauma or an infection.

From the examinations by EWING, PERTHES, RAHM and others we learned that the histological picture of bone injuries caused by X-rays shows an impairment of the vessels, a reduction of the number of the osteoblasts and the development of sclerotic connective tissue in the marrow cavity. When examining the irradiated bones of the test dogs with special regard to this fact, we observed most serious alterations even in those cases in which they had received doses not causing serious damage to the skin, as for instance 2 series of 12 times 300 units in intervals of two months. Even the macroscopic inspection of the cuts of bones which in their external aspect as well as in the X-ray picture revealed no alterations, did not show a normal red bone marrow but a marrow which was yellow in color.

The histological examination shows a fibrous marrow in which neither red nor white blood corpuscles are observed. In contrast to the other side which was not exposed to the X-rays the cells of the bone substance hardly assumed any stain. The alterations are particularly serious in its cell nuclei.

In order to demonstrate that even small doses influence the bone, at least as regards its functional alteration, the left fore-legs of test dogs were irradiated with 6 times 400 units (the conditions of the irradiations were the same as above) and MARTIN's and MUELLER's experiments were repeated with the irradiated extremities.

Subsequent to the irradiation, in five dogs, 2 cm long pieces of bone were resected from the left radius with the dogs in Somnifen narcosis in much the same way as in the control tests during which the bone was not exposed to X-rays. During these operations any lesion of the ulna was most cautiously avoided. All wounds, even those which had been irradiated came to a healing without any infection. In the cases which had not been irradiated, distinct periosteal depositions were observed on the ulna 2 to 3 weeks later. After a lapse of 6 weeks they attained a considerable size. In the irradiated cases neither bony apposition nor alterations of the bone structure were observed during frequent consecutive X-ray controls.

In the skin a slowly developing alopecia was observed. Other reactions could not be proved contrary to the findings in the intensely irradiated dogs in which exudative dermatitis or even ulcerous dermatitis were observed. The general condition of all animals however was normal.

<u>Four weeks later, in one case after a lapse of 8 weeks, a fracture was clinically observed in all test animals.</u> In each case trauma could be excluded. The X-rays taken immediately after this observation proved that we had to deal with typical <u>fatigue fractures</u> of the ulna which was clearly noticeable <u>by the absolutely</u> transverse course of the fracture cleft which displayed no comminution. Also after that time the ulna did not show any or only negligible periosteal reactions and furthermore no alterations of the bone structure were observed.

The dogs were kept under observation for half a year, some of them were killed earlier primarily in order to enable histological studies of the connective tissue around the fracture. But even after half a year no alteration of the connective tissue was observed which could be attributed to the effect of the irradiation.

In no case did fatigue fractures of the ulna show a marked straight forward formation of callus so that in no case a bony healing was obtained.

<u>Zones of reconstruction in the ulna were not observed in any case of a fracture following large doses of X-rays.</u>

The following picture which shows the distinct difference between the irradiated cases and those not exposed to the X-rays should illustrate once more the findings discussed above.

a

b

Illustration 13.

After the resection of the radius of a dog (a) a thickening of the ulna in the sense of a functional reconstruction is observed on the side opposite the resection site which does not appear after irradiation. Instead a fatigue fracture develops (b). (According to BADE and KUENTSCHER).

After the resection of the much stronger radius the ulna can no longer stand the normal strain when periosteal deposits do not develop; all the more because a tension develops on the place opposite the resection site.

The most remarkable feature of the experiments however seems to be that doses which cause an epilation but no other alterations of the skin and which do not cause an alteration of the connective tissue, lead to a complete suppression of the functional bone reconstruction. DAHL was correct in saying that the bone, principally however its normal osteogenic tissue, is much more sensitive to X-rays than the skin and the connective tissue. In rat tests with doses which produced temporary dermatitis with late alopecia of the skin and stronger doses he produced permanent sterilization, spontaneous fractures and finally necrosis of the bone after a complete breakdown of the blood supply to the afflicted limb. By applying smaller doses he observed a paralysing effect upon the osteogenesis. In his analysis of ray damages in humans he came to the conclusion that a coherence exists with his findings in animal tests. Contrary to the hitherto generally accepted theories, DAHL's and my own results, as well as those of other investigators led to the conclusion, that bone belongs to the group of the radiosensitive organs. As to its regenerative and functional power the bone is even most sensitive so that as regards this its sensitivity does not depend on the properties of the connective tissue in it but

rather is higher than that of the latter.

The experiments prove that the functional transformation of the bone may be suppressed by X-ray irradiation. The ulna reacts to the increased strain and the deformation with an apposition of bone which is very distinctly shown in Illustration 13. Such an apposition of bone is not observed after irradiation and thus the fatigue fracture develops just as during a precipitate training of recruits the fatigue fracture occurs because the functional apposition of bone has not yet developed. The latter process takes at least 8-10 weeks. A bone which has received a higher dosis of X-rays must not be expected to show any regeneration. Resections, transplantations, plastics, etc. should therefore not be made with such bones, because no normal healing can be expected. (In this connection I would like to refer to chapter VII in which it is discussed that in cases of that kind the marrow nail as a permanent support may still be a means of aid). The tests unequivocally proved that in fatigue fractures we have to deal with a special fracture mechanism which is equal to the dynamic and static mechanism. The development of the zone of reconstruction is a biological reaction of the bone tissue which may be completely suppressed by irradiation.

"Mechanically produced" diseases of the bones and joints.

Both groups of disease are due to "mechanical" conditions and therefore are equal in localization. To this field belong quite a number of diseases of spongy bone and the articular heads. Sometimes the fatigue fracture constitutes the local manifestation of the diseases while in other cases they appear as zones of reconstruction. The histological impairment of the bone in fatigue fractures was studied by SCHUERMANN in a large number of cases. He often observed only an infraction of the upper compacta layer. Principally he observed cellular infiltrations in the damaged area and fresh hemorrhage. These are pictures of the kind seen in fractures. In the zones of reconstruction we find the well-known alterations: Destruction of the old bone lamellae by lacunary resorption and its replacement by a plexus-like bone which in the beginning does not contain any calcium. Finally I would like to point to the following fundamental difference: In fatigue fractures an abundant formation of callus occurs even in those cases in which we have to deal only with an infraction. Very often the alteration taking place in the bone is first observed by that formation of callus. Contrary to that in the zone of reconstruction no, or only very slight, formation of callus is noticeable. LOOSER himself was of the opinion that regarding the clinical and roentgenological symptoms the zones of reconstruction must not be considered as fractures.

In all cases the "diseased areas" stand vertical to the causative forces i.e. vertical to the tension maxima corresponding to the traction of the entire muscle mass. (See Illustration 14 a and b).

Illustration 14.

a

shows the traction cracks on the radius when under strain in the direction of the muscle traction, i.e. a strain aiming at "Zerknickung" (angulation) (according to KUENTSCHER).

b

Scheme of the position of the diseased areas in relation to the direction of the muscle traction in zones of apposition and fatigue fractures.

Excepted from this rule are the reconstruction zone and fatigue fracture in the neck of the femur because of the different location and course of the tension maxima in the neck of the femur as pointed out previously (Illustration 3 and 4).

To this field belong: The disease of the scaphoid bone first observed by KOEHLER and called after him (KOEHLER I) and the disease of the head of the second metatarsal bone (KOEHLER II). In rare cases also the head of the third metatarsal bone is involved and in one case even an involvement of the first metatarsal bone was observed. To this field belongs also KIENBOECK's disease of the semilunar bone of the hand and other diseases which are less frequently observed, as for instance the malacia of the sesamoid bone (RENAUDER). Rare cases of similar diseases in the sternum and also in the acromial end of the clavicle (FRIEDRICH, ECKER) and in the head of the humerus (PALMER,

BUSCH), in the unciform bone and greater multiangulum (BUCHMANN). Similar changes in the epiphysis of the terminal phalanx of the fingers were observed by KONJETZNY and BRANDES. Similar changes in the epiphysis of the central phalanx were also observed (LEHMANN, THIEMANN and others). In the lower epiphyseal line of the femur malacic processes were described by NILSONNE, HANSEN and LANGENSKJOELL. BURCKHARDT refers to one case of similar alterations in the tibia head.

This also refers to certain cases of patella bipartita which in this connection are known under the term osteopathy of the patella. MAU, ROSTOCK and others observed zones of rarefaction and bone necrosis in the patella. The numerous cases of epiphyseal necrosis of the os calcis are probably also sometimes due to a genuine aseptic necrosis.

SILFVERSKIOELD for instance gives an account of a posttraumatic necrosis in the cuboid bone with alterations resembling the local malacias. The calcaneus was simultaneously afflicted.

The author has dealt with such a disease in connection with II cuneiform.

Finally there is a close resemblance of these diseases with PERTHES' disease of the hip joint and with the osteochondritis dissecans in the elbow and knee joint and other joints. All these cases are characteristic changes of the epiphysis. Through AXHAUSEN's investigations one knows that they are non-specific aseptic necroses (Epiphyseal necrosis).

Since the problem was raised by KOENIG the question was how this disease develops and a great many authors are of the opinion that they are due to mechanical factors. Some of the authors assume that the vascularization was disturbed in the corresponding region of the bone which later becomes necrotic. This may occur if the vessels became obstructed by an embolus (infarction) or if there is an infectious toxic damage of the vessels.

KAPPIS, however, points to the fact that this does not explain hemorrhages which are so frequently observed in these necroses. Hemorrhages of this kind must be of traumatic origin which speaks in favor of the theory of the traumatic origin of the necrosis. In many cases it is possible to trace such a trauma in the previous history, in most cases however, no such trauma was traceable. In almost all cases of malacia a transverse fissure is observable which might be interpreted as a fracture cleft. The course of this fracture cleft does not correspond to the course of other fracture clefts developing at these spots. In most of the cases the trauma has occurred long ago. Moreover, the patient's statements as to a previous trauma are in most of the cases not reliable. W. MUELLER interprets the cleft as a regional zone of resorption which has developed in the course of time on the base of mechanical conditions. This zone is the regional reaction of the tissue to mechanical factors acting upon it.

This is in conformity with the developing of LOESER's zone of reconstruction at the diaphysis of the bone. This theory was also adopted by HEINE. According to BRUCKHARDT the most essential thing is that in this case a large number of minor injuries of the tissue develop and even small disruptions may occur in the course of time. According to BURCKHARDT's theory we have to deal here with effects of pressure which are due to absolutely locally conditioned angulations and to an anemia of the bone trabeculae and probably also with a direct pathological compression of the bone cells. The absence of bone regeneration is explained by the assumption that this regeneration is not started by the necrosis of the bone cells but by the cells of the marrow. This theory was suggested to him by the observation made in congelation tests of the bone. Such a damage of the marrow however is said to be not present here. ROESSNER demonstrates that the alterations in osteochondritis are similar to those pictures which are observed in the effects of a piston on soft iron produced by FREY's caustic method. REISCHAUER points out that these pictures of osteochondritis are similar to the effects which may be produced in steel by means of BRINNELL's hammering method. The author was in a position to show that in case of a continuous prolonged rhythmic strain on the joint ends of the bone by means of an electric motor, cap-like fracture planes (shape of a priest's cap) develop which correspond to the zones of malacia. In these tests the fractures appeared as fatigue fractures. The bone trabeculae of the joint ends are angulated many thousand times by the pressure and regain their former shape as many times because of their elasticity until finally by the process of loosening a disruption and with it a fracture occurs. A fracture of this kind is observed in the zone of greatest deformation.

The question why in one case a PERTHES' and in the other a KOEHLER II disease develops may be explained in different ways. The localization of fatigue fractures in long shaft bones depends only on the question as to which part of the muscle mass was in action. In case of strenuous marching the metatarsal bone and in case of wading in mud the neck of the femur will break. As mentioned above, in none of these cases was any local or general disease observed which would have given the description to those fractures. The only striking thing was that only people not accustomed to such strain and prevailingly those with long, thin bones were afflicted with the disease. It is a matter of course that under the same weight bones of that kind are subject to a greater deformation than short thick bones.

As to the epiphyseal necroses we must take into consideration that there must be a second local factor which may explain why it is just the afflicted articular head where the alterations develop. On the one hand inherited local dispositions are possible here, while on the other hand a local reduction of the mechanical stability of the bone substance through toxic conditions as through disorders of growth occur. Finally trauma may also be blamed for such an impairment.

Even a very small infraction has the effect of a notch in which a considerable concentration of tension develops, which may give rise to the development of an extensive fatigue fracture. Surprisingly enough necrosis of the epiphysis occurs at certain ages as for instance KOHLER I, 5 years, KOEHLER II between 14 and 18 years. The fact that exclusively youths are afflicted with this disease may be explained by the fact that in juvenils the bone substance is bent much more than at a later age and therefore the deformations are greater in this case.

C. The Mechanical Element in the Fracture Healing.

All this was discussed in such detail because it is, of course, of the utmost importance for the comprehension of the process of fracture healing and the factors disturbing it. The mechanical element is of decisive importance for the development of the callus which leaves all other factors, such as infection or hormonal influence far behind. In no case will it be possible to bring a pseudarthrosis to a healing by the administration of hormons, but only by establishing stable mechanical conditions. The callus must be protected against harmful tension maxima. It needs no further explanation that a fracture cleft running vertically through the neck of the femur and in this way corresponding to a fatigue fracture in any bone, heals badly or not at all, since, as already mentioned above, there exists as a result of the notch effect a tension maximum at each fracture site. In addition due to its softness the callus is subject to a greater deformation and finally young tissue is more sensitive to all harmful effects. Much the same applies to the transverse fractures of the long shaft bones. It is well known that contrary to the elongated oblique fractures, the plain transverse fracture of the humerus has a tendency to develop pseudarthrosis. In this way we easily understand that we have to distinguish between "mechanically favorable fractures" and "mechanically unfavorable fractures". PAUWELS was the first to show it clearly in fractures of the neck of the femur. The shape of this fracture as well as that of any other is determined by the nature of the trauma and by the point of impact which caused the fracture. We must take into consideration however that in almost all cases the muscle traction is of great importance. With only few exceptions (as for instance when under the influence of alcohol) the bone is subjected to a great angulating pressure caused by its surrounding musculature, which is combined with the dynamic force of the trauma. If in this way the vertical fracture cleft develops, considerable traction tension maxima will develop in the fracture cleft which are due to the bending. If, as usual, the cleft is complete, perpendicular and shearing forces causing lateral displacement will prevail. If the fracture cleft runs in the horizontal direction - which unfortunately is observed only in rare cases - the compressive forces will prevail. This is a mechanically favorable fracture. The share of the compression, traction and shearing forces is determined by the inclination of the fracture plane from the horizontal (see Illustration 15.

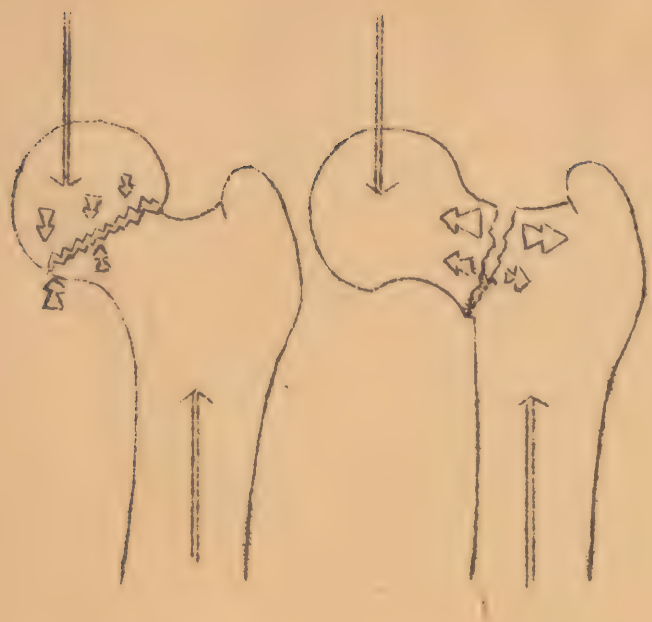


Illustration 15.

Relation of the compression traction and shearing forces in case of a horizontal (favorable) and a vertical (unfavorable) fracture of the neck of the femur, according to PAUWELS.

As already mentioned above in detail the traction forces and in addition to them the shearing forces act as separating forces and therefore they are unfavorable for the healing of the fracture, as has been thoroughly proved in practice. The prevalence of the compressing forces in the fracture cleft is favorable for the healing process. The compressing force prevents the development of disuniting forces, because of the always slightly jagged surface of the fracture planes. There is no doubt that the development of compressing forces in the callus acts as a functional stimulant for the transmutation in the bone tissue. In adult bone this corresponds to ROUX's law which says that the compressing forces act as a formative stimulant upon the osseous substance whereas the perpendicular and shearing forces cause a reduction of the bone. From the teleological point of view this seems to be the most appropriate reaction, because it is the function of the bone to transmit compression forces and to resist them. The formation of connective tissue through the traction forces seems to be quite suitable in view of the general structure of the body as the transmission of the traction forces is the function of the connective tissue. This is most disadvantageous however, in the special case of the vertical fracture cleft of the neck of the femur. PAUWELS gave practical proof for the correction of this opinion by realizing an audacious idea. He transformed the unfavorable vertical fracture cleft into a favorable horizontal cleft by cutting out a wedge performing the

subtrochanteric osteotomy. In this way it was possible to achieve the healing of the vertical fracture (Illustration 16).

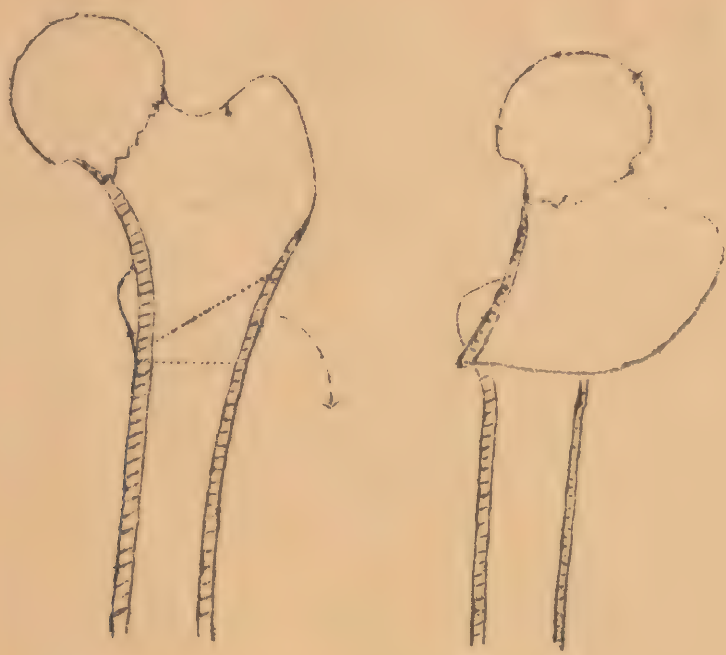


Illustration 16.

Scheme of PAUWEL's operation. Transmutation of the mechanically unfavorable vertical fracture cleft in a favorable fracture cleft by subtrochanteric osteotomy.

By the insertion of a nail in the neck of the femur the flow of the forces is immediately altered, while this cannot be accomplished by the use of a plaster cast, because the tension and action of the muscles in the longitudinal direction of the bone cannot be eliminated. As long as the nail is firmly seated it absorbs all shearing forces. The more proximal it is located in the cross section of the neck of the femur the better it transforms the prevalence of the traction forces into the prevalence of the compression forces. A nail located very far distally in the neck cannot fulfill its mechanical and biological purpose because the traction forces prevail in the major part of the fracture cleft (see Illustration 17).

In much the same way all fractures may be classified either as mechanically favorable or mechanically unfavorable according to the position of the fracture planes to the total component of the muscular traction. According to the scheme given in Illustration 14b the transverse fracture cleft on the shaft of the long tube bone is unfavorable. As a result of the angulating strain considerable bendings in every direction are found which in all cases provoke high tension maxima on the opposite side almost filling the entire fracture cleft.

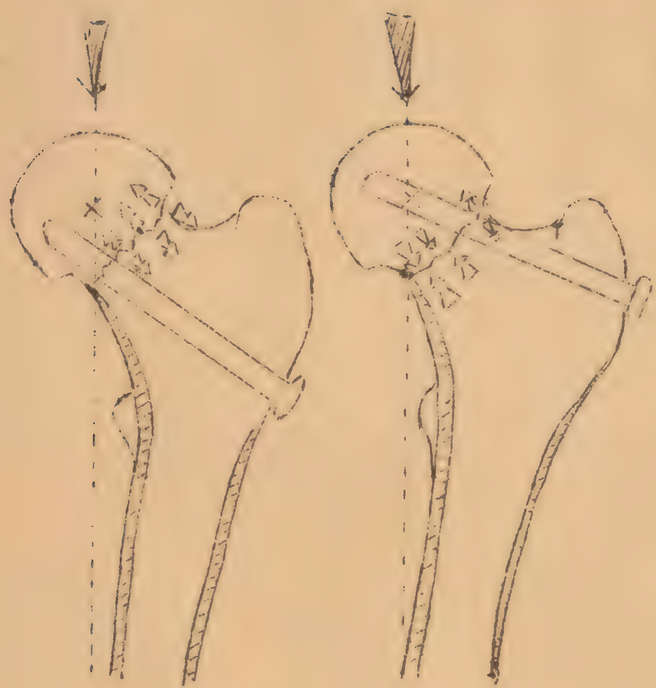


Illustration 17.

Relation of the forces in the fracture cleft after nailing the neck of the femur (according to PAUWELS).

On the other hand the oblique fracture is all the more favorable, the more vertical the fracture cleft is. In case of a comminuted fracture we will always find oblique fracture clefts with a most favorable prognosis as to restoration. It is therefore possible to transform a transverse fracture into a mechanically more favorable fracture by splintering the ends of the fragments (according to KIRSCHNER). This method in addition has a stimulating effect on the formation of callus, a matter which will be dealt with in the following chapter. If in case of such a primary or secondary comminuted fracture a pseudarthrosis develops because of an insufficient fixation, the pseudarthrosis cleft must run transversely corresponding to the site of the tension maximum.

This is actually the case and once again confirms the above opinion (compare Illustration 18).

These mechanical conditions cannot be eliminated entirely even by the application of a plaster cast. Even in the not padded plaster cast (BOEHLER) the angulating strain is not compensated. The action of the muscles cannot be immobilized and in the soft parts the fracture ends cannot be immobilized to such a measure that no movements in all directions are possible. The musculature yields in the lateral direction and the subcutaneous connective tissue and the skin are compressible (see Illustration 19).

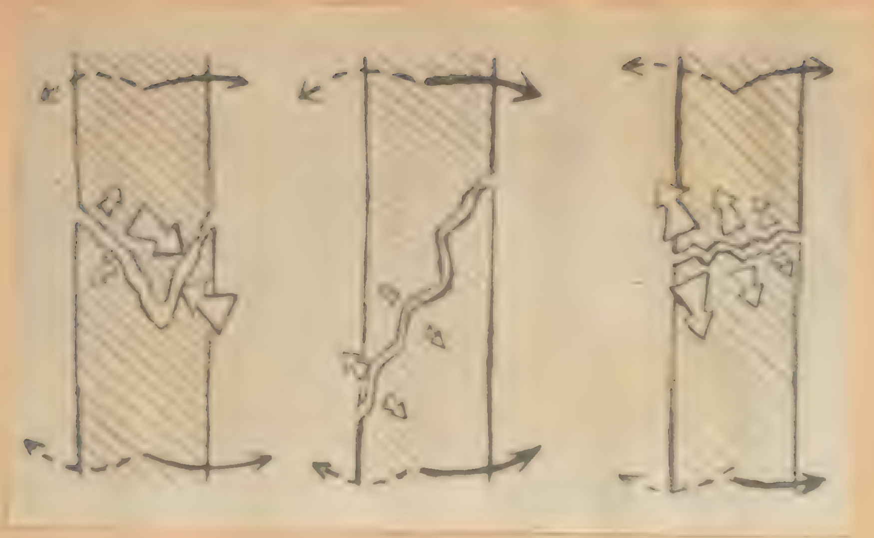


Illustration 18.

Scheme of the relation of the forces in the fracture cleft of long bones.

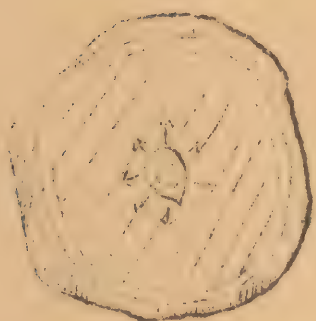


Illustration 19.

Cross section of the central part of the thigh in the plaster cast. The bone may be moved to a certain extent in any direction.

It is a matter of course that harmful tensions will develop in all cases in which the plaster cast does not fit well and consequently does not fix the fragments sufficiently or if the cast becomes loose because of a muscle atrophy. It is absolutely clear that the unpadded cast of BOEHLER is mechanically superior to the padded cast. Especially harmful tensions develop when changing the cast so that the demand for a long lasting uninterrupted immobilization is well founded not only by the practical experience but also from the theoretical point of view.

It is a matter of fact that with an opposed motion of the fracture ends shearing forces develop. These may also occur as a result of rotation. There is much less immobilization in an extension bandage. Consequently much higher tensions may develop. This gives an explanation for the contention of numerous authors that through the introduction of the extension treatment pseudarthrosis is becoming more frequent. In the lower leg a further very interesting mechanical factor is of great importance and it is responsible for the development of a great number of pseudarthroses of the tibia; this is the obstructing effect of the fibula. It was proved by experience that leg fractures in which the fibula is intact show a far greater tendency to develop pseudarthrosis than those fractures in which both bones are broken.

The fibula, if it is intact, forms a fairly firm mechanical unit with the proximal and distal fragments. As soon as the musculature is under tension, the thin flexible fibula will be rather markedly deformed so that the fracture planes are pressed together. As soon as the muscle traction relaxes the fibula will regain its former length and thus disrupts the fracture cleft of the tibia. All this means that in the entire extent of the fracture cleft traction forces develop predominantly. (See Illustration 20).

It is easy to understand that the above mentioned effect is as strong in case of an oblique fracture cleft as in a transverse cleft. There is no doubt that by the disruption of the fracture cleft a lateral displacement in it be all the more easy, as no effective interlocking of the fracture planes is possible. This means that shearing forces develop which in other cases would be consumed by friction. This effect however is less important in comparison to the first one. That these frequently observed pseudarthroses are due to mechanical conditions is proved by the daily observations of the surgeon. The obstructing effect of the fibula is eliminated by resection of a part of the fibula and most of the cases of this kind come to a good healing after a suitable fixation. Therefore it does not make any difference at which spot the fibula is resected. In what other way is it possible to explain the effect of this operation?

a b

Illustration 20.

Obstructing effect of the intact fibula in case of a tibia fracture.

a) if the musculature is under tension (strain) the fibula gives way elastically thus causing a compression of the callus,

b) after relaxation the fibula extends and disrupts the fracture cleft.

Due to the characteristic shape of the marrow cavity of the tibia a stable fixation is frequently not obtained by the marrow nail (see chapter V). The obstructing effect of the fibula may therefore also be observed in cases treated with the marrow nail method - though less frequently- particularly because the patients subject the limb to tension when walking. Therefore the author recommends to fracture the fibula in all cases of fresh tibial fractures and to resect it in all cases of a marrow nail osteotomy of a tibial pseudarthrosis (see chapter VI). In both cases the reposition will be greatly facilitated by such an intervention.

There is no doubt that the elastic deformation of the tibia will be considerably greater in a walking cast, than in a plaster cast which confines the patient to bed. But in all these considerations one must bear in mind that even the slightest deformations show very considerable effects, as was shown in detail in the beginning of this chapter. Such movements in the longitudinal direction amounting to a fraction of a millimeter only can by no means be prevented even by the best fitting plaster cast, as the varying tension of the musculature is sufficient to permit movements of the fracture ends. Such an obstructing effect cannot occur with a marrow nail because it does not recoil, i.e. its deformation is so small that it is of no practical significance. As an example I would like to refer to the case of the 38 year old patient G.M. who had suffered a fracture of the fibula and tibia. The tibia fracture did not show any formation of callus eight weeks after the accident. Only the fibula had come to a healing (see Illustration 21). By the effect of the closed nailing (Chapter Vc) the nail jammed in the endosteal callus of the distal fragment and due to the further driving in of the nail the fragments were separated from each other so that we had to deal with a cleft of 1½ cm. Despite the fact that in this case no noteworthy tendency to form callus was observed the slight intervention as is the percutaneous insertion of a marrow nail and the resection of the fibula sufficed to produce the formation of so much callus that even this large cleft was completely bridged over by callus. The gap was certainly not closed because of the loosening of the nail and by the consequent pressing together of the fragments by muscle traction. This is revealed by the fibula defect which was also bridged over by callus and the length of which remained completely unaltered (see Illustration 21).

a b

Illustration 21.
An 8 week old tibia fracture did not show any formation of callus in the cast.
a) The fragments were driven apart during the marrow nail operation because the marrow nail jammed in the distal fragment. No jamming together due to the marrow nail.
b) The fracture cleft was bridged over by callus 8 weeks later.

There are many examples of this kind. Particularly impressing is one case which I owe to Dr. EHRLICH. In this case of a fresh thigh fracture the fragments were driven apart 1½ cm. by the nail which was too thick. Also in this case the gap was filled with bone so that unintentionally an elongation due to the marrow nail was achieved (see Chapter VI). The functional result obtained was very good, because the pa-

tient was able to get up early and to subject the limb to weight bearing very early. The elongation of the limb amounted to only 1½ cm.

a a a b b

c c

Illustration 22.

Disruption of the fragments by the marrow nail which is too thick.
a) The fracture cleft is gaping for 1½ cm. (Nov.11,1941).
b) (3 April 1942) The gap is bridged over by callus. Periosteal rarefaction resulting from effect of too much pressure of the nail could be seen in original X-rays.
c) (1 July 1942) Heavy callus bridge clearly seen. On 2 February 1943 after extraction of the nail good healing was evident. X-ray unfortunately not available for reproduction.

All these cases prove that the marrow nail has certainly no harmful effect upon the formation of callus.

Finally, the author asked D. SINN to examine a number of pseudarthroses as to their origin. He clearly found that mechanical causes had by far outnumbered all the other causes as for instance: infection of the fracture cleft, repeated operations or general causes such as marasmus, diabetes, lues, etc.

All harmful tensions can be completely eliminated by means of the marrow nail. Thus it is the method of choice for the treatment of pseudarthrosis. This treatment is causal.

The marrow nail not only eliminates the notch effect at the fracture site but it also consumes all the tension maxima so that the callus can develop in a mechanically undisturbed environment. Only a very slight displacement of the fragments in the longitudinal direction of the nail is possible in the sense of a pressing together of the fragments. Hence only pressure tensions develop everywhere in the fracture cleft. This means that any fracture, no matter whether it is a transverse or a longitudinal fracture is reduced by the marrow nail to a mechanically and biologically favorable fracture (see Illustration 23).

The pressure tensions become slightly greater in the course of weeks because the nail becomes loose and consequently permits an increase of motility in the longitudinal direction. Lateral displacement however as well as bending or shearing motion is impossible because of the length of the nail. But even after a lapse of 8 weeks the longitudinal displacement is extremely small when the efforts necessary to remove a femur nail 8 weeks after its insertion (see Chapter V) are considered.

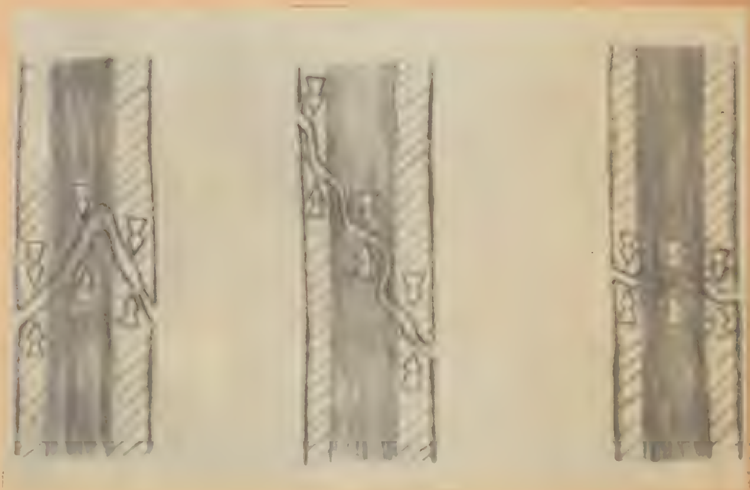
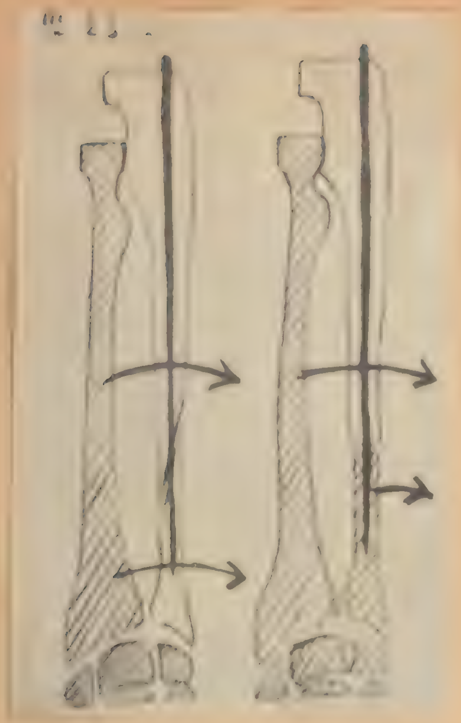


Illustration 23.

Mechanical conditions in the fracture cleft. Only pressure forces are observed. All types of fractures are reduced to "mechanically and biologically favorable" fractures.

All this is only valid under the condition that the marrow nail held with a great force by its proper elastic forces as well as by those of the bone really forges a stable union with the bone. Only in such a case can we speak of a successful marrow nailing and only then have we to deal with a true marrow nailing and only then are we entitled to speak of a marrow nailing! If such an elastic jamming together does not exist traction and shearing forces may develop in the callus and that all the more the greater the disproportion is between the diameter of the marrow nail and the marrow cavity. In that case rotation of a fragment round the nail axis may occur but not necessarily so. In case of an oblique fracture for instance such a rotatory movement is not possible, provided that the fragments are not torn asunder, this is prevented by the muscular tension. In a transverse fracture with the nail loosely seated in the cavity a rotation is easily possible. (See Illustration 24).



a b

Illustration 24.

Rotation due to a loose nail.
a) impossible in case of an oblique fracture
b) possible in a transverse fracture.

Any rotation of the fragments causes the development of considerable shearing forces in the fracture cleft. Thus it is adviseable when creating artificial fracture planes that means with resections, to produce, if possible, such oblique planes. This applies particularly to the forearm where, in comparison to the other limbs the relatively strongest rotation musculature ex ists and where the rotation is of the greatest functional importance.

There is also a bending through angulating forces which however, because of the length of the nail is not very extensive, as the angle is limited by the length of the nail. Only in those cases in which the nail is too short a considerable bending and with it traction tension in the callus occurs. (See Illustration 25).

a b

Illustration 25.

Extent of bending in case of a marrow nail which is too thin.
a) If the length of the nail is correct,
b) if the marrow nail is too short.

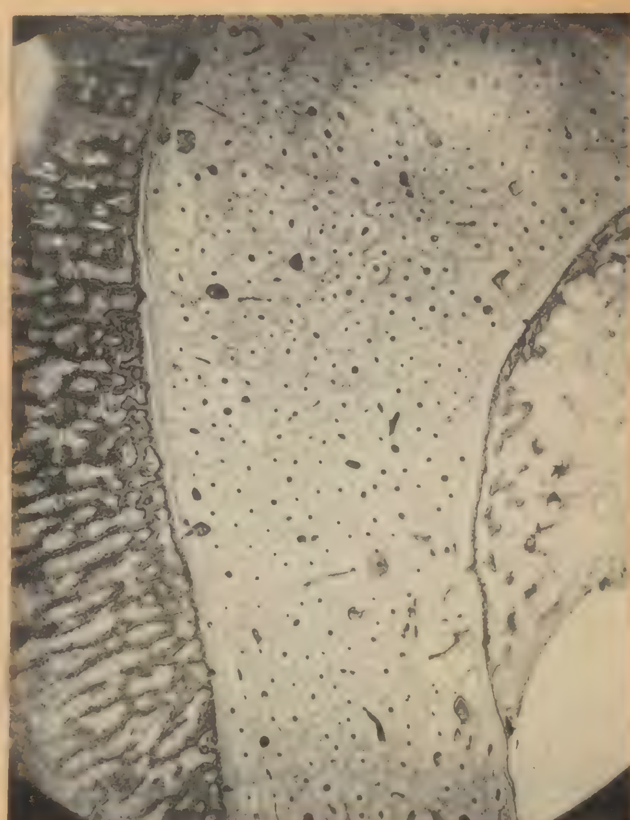
In all these considerations the marrow nail is regarded as an absolutely rigid body with no deformations. This, of course, is not the case. As the marrow nail is made of steel its deformation is negligible in proportion to the strain, if its cross-section has the normal shape. Only if there is an extreme disproportion, if, for instance a much too weak marrow nail was used for the femur, the deformation of the nail could be of real importance. The existence of such a mechanical-biological effect was proven by F. GRIESSMANN and H. REICH in very impressive experiments. Comparable histological examinations left no doubt that due to its structural validity the callus in marrow nailed fractures is superior to the callus formed during treatment in the plaster cast because is is

formed under conditions of mechanical rest.

The above mentioned experiments were made in dogs. By means of the osteoclast in each case both tibiae were fractured without injuring the integument and in such a way that the fractures were as equivalent as possible, without any marked displacement. One of the legs was treated with a plaster cast while the treatment of the other one consisted of closed marrow nailing (VII D). In those dog experiments in which the experiments were continued over a long period of time, corrections were sometimes made of the position of the fragments which in the beginning was excellent, and the plaster casts had to be replaced by new ones. These are measures similar to those applied during the treatment of man. The dogs were killed 1, 2, 5 and 6½ weeks after fracturing. The most conspicuous observation in the histological picture was the absolutely correct organization of the callus and bone formation in the marrow nailed fractures contrary to the irregular structures observed in the fractures treated with plaster cast. The bone trabeculae are arranged in absolutely regular tracts, as already pointed out by the author in his first publications on his animal experiments. This indicates that the callus developed under conditions of an absolute rest. This regularity doubtlessly means that the callus must be of a greater mechanical value (see Illustration 26).

Both pictures (Illustr. 26 a and b) after GRIESSMANN and REICH.

Illustration 26a.
14 days old tibia fracture in a dog - treated with a plaster cast



According to GRIESSMANN and REICH these tests showed the following results: While in fractures treated with the plaster cast not only the osteogenetic elements take part in the stabilization of the fractured bone, the parosteal tissue does not participate in it when the marrow nailing method is applied. The tests proved that the periosteum plays the pre-eminent part for the healing of the fracture.

Illustration 26b.
14 day old tibia fracture in a dog treated with the marrow nail.

The periosteum of the marrow nail treated fractures shows a considerable formation of new bone far distant from the fracture site. In the corresponding area of plaster cast treated fractures a periosteal reaction cannot be observed.

At the fracture site itself a good periosteal formation of bone is observed with both methods of treatment. It is striking, however, that the callus in plaster-cast treated fractures creates the impression of an irregular and plexus-like structure whereas marrow nail treated fractures show a regular and radially arranged structure of the callus.

In both cases after a lapse of a certain period of time the callus reacts with signs of lacunary resorption which with the plaster cast method appear at an earlier time and on the whole are more widely distributed throughout the bone where they are more pronounced.

In marrow nailed fractures the bone marrow shows the formation of medullary callus along the entire extent of the marrow nail. The nail bed itself is surrounded by a connective tissue sheath, that means delimited by connective tissue. In cast treated fractures the formation of medullary callus is observed only in the fracture zone, contributing together with the periosteum to the intermediary consolidation of the fragments.

The structure of the callus formed in marrow nailed fractures is absolutely regular and leads directly to the consolidation of the fracture. Due to its high structural value it is much superior to the callus formed in cast treated fractures. <u>The decisive fact is the structural quality of the callus and not its quantity.</u>

KROMPECHER observed that the bone usually reacts with a chondrogenous development if it is subjected to pressure strain, while it shows a desmogenous reaction after traction strain, and where neither traction nor pressure forces arise an angiogenic development of the bone is to be expected under normal conditions. In dog experiments he produced leg fractures and perforated the bones proximally and distally by means of KIRSCHNER's wires in the transverse direction.

In one series of experiments the ends of the fragments were pressed together by means of these wires, while in another they were pulled apart. KROMPECHER is of the opinion that the same effects are to be observed in the process of the healing of a fracture just as in the process of the normal development of bone. In those cases in which the fragments are pressed together he observed a cartilaginous preformation of the bone and in the cases in which traction forces existed a transmutation of the undifferentiated mesenchymal germinal tissue to the temporary connective tissue callus. During this process reserve cells remain between the collagenous fibers which are transformed into osteoblasts and which envelop the fasciculi of connective tissue with bone substance. Due to its structure chondral callus is particularly suitable for withstanding pressure, the desmoid callus, however is not. KROMPECHER's observations were supported by findings in a fracture, which had healed in angulation. In that case there was a desmoid healing of

the convex side under traction and at the other side, which was under pressure, there was an enchondral fracture healing. GRIESSMANN and REICH are correct in criticizing this conclusion. With KROMPECHER's arrangement of the experiments it is not possible to produce a pure traction or pressure strain in the fracture cleft. Consequently in all "pressure tests" traction or shearing forces will simultaneously develop. Only with the marrow nail is it possible to provide proper experimental conditions and to exclude all perpendicular and shearing forces. In their above described tests GRIESSMANN and REICH observed that in marrow nailed fractures desmoid callus is formed under pressure. This is in accordance with the generally accepted opinion in pathology, namely that desmoid callus develops during fracture healing. In all experiments, during which the fractures had been immobilized by a plaster cast contrary to that they found an abundant formation of cartilage, especially parosteally, which they traced back to the insufficient elimination of the perpendicular and shearing forces.

This author would also like to point to the fact that in KROMPECHER's experiments the callus is not under direct traction because the traction is consumed by the soft parts, principally by the musculature.

It was shown that the final development of callus almost exclusively depends on the forces acting in the fracture cleft and therefore depends on the mechanical conditions. The author would not like to create the impression of considering the healing of a fracture as a purely mechanical process. This would be too superficial. But rather it is a fact that such a mechanical analysis leads deeper into the biological problems, since there is as a salient problem the question: Why does a mesenchymal cell form a hard pressure resistant calcium sheath when it is under pressure and why does it in the other case produce connective tissue fibers? We do not even know whether it is the force itself which determines the cell to do that or whether it is deformation caused by it.

The mechanical analysis is essential for the understanding of the processes taking place during the healing of the fracture and in the same measure for the evaluation of the biological effects in the various methods of treatment.

Here it becomes apparent that the marrow nailing operation is so to speak the logic conclusion from the findings obtained so far by research work and that it creates ideal biological conditions at the fracture site. But only a certain section of the conclusions could be discussed here to avoid an undue volume of this chapter and many a valuable publication could not be referred to. A detailed description of those problems may be found in W. BLOCK's excellent book "Die normale und gestoerte Knochenbruchheilung".

The question now remains to be discussed, how it actually comes to the formation of that callus.

D. The Formation of Callus.

Through the fracture of a bone the ends of the fragments or their surroundings are suddenly induced to form a special tissue, the callus tissue. After that instigation the process develops automatically. After a certain period of time this complicated development of tissue proliferation comes to a standstill. According to the mechanic conditions the tissue forms either bone tissue or connective tissue. With this the automatism is exhausted. The process may be either delayed or entirely suppressed by means of X-rays. In the extremely extensive literature about callus there is no agreement on the so very important question of what incites the development of callus.

Only that is certain that if we want to set this automatism in motion or if we want it repeated - as for instance in case of a pseudarthrosis- the only means to achieve that effect is to produce a fracture again, either by using KIRSCHNER's comminution method, BRANDIS' sawing, or BECK's drilling, etc. All these interventions actually do not represent anything else but the production of larger or smaller bone fractures. The stimulus causing the formation of callus is according to the opinion of many authors either due to hormonal or chemical effects of substances which are found in the fracture hematoma or which originate from the decay of tissue. Lastly such stimuli are said to originate from the bone marrow, or they are ascribed to the acid reaction of the tissue caused by the inflammation. Through the stimulation of such stimuli, namely by the acidification of the tissue, the injection of hormons, hormonoids and vitamins, homogenous blood, etc., one does not succeed in similarly stimulating the formation of callus, as it results from bone fracture and the above mentioned bone destroying intervention. The second very important question cannot quite clearly be answered. This question is where the formation of callus starts, whether in the marrow, in the periosteum, in the bone substance itself or in the surrounding connective tissue. DUHAMEL was the first to discover the bone forming properties of the periosteum and DUPUYTREN ascribed the property of forming callus to the bone substance of the fracture plane and to the surrounding connective tissue. The difference of opinion on this subject between BIER and LEXER is well known. As pointed out by BLOCK, BIER did not attach exclusive significance to the marrow nor LEXER to the periosteum, but both only predominance. Just as in so many processes of the living organism, here as with the stimuli provoking the formation of callus general causes and possibilities are coordinated to each other and act simultaneously. The recently acknowledged opinion is that mesenchymal cells originating from different tissues form callus and thus can differentiate into bone, cartilage, or connective tissue.

Callus without bone fracture.

With his first marrow nail operations the author observed that in some cases enormous quantities of callus developed. This was nothing unusual due to the elimination of all harmful mechanical effects and the intact local and general blood circulation as a result of the early exercises a good formation of callus had to be expected from the very beginning. In many cases however, all this was not sufficient to explain the development of such considerable quantities of callus as had been observed in so many cases after the use of a marrow nail. When studying the X-rays one rather is under the impression that the nail inserted in the marrow has a greater stimulating effect, as for instance formation of callus extending to the trochanter minor is observed with fractures located in the middle of the femur. In this case the picture of the so-called "periosteal deposition" frequently develops.

In dog experiments the author made the attempt to produce angulations by using spring blade marrow nails and in this way it was possible to prove that such a stimulating effect is possible. Originally these tests were made in order to find out whether or not it would be possible to correct angulations and bendings of the long bones, which occur as the so-called delayed sequelae of rickets, by using appropriately shaped nails, as they cannot be eliminated otherwise in a satisfactory manner. In our dog experiments it was attempted to produce alterations of the shape of the bone in the sense of angulations. For this purpose strong leaf springs were percutaneously inserted into the marrow cavity and the bending force of the springs could be modified by using leaf springs of different strength. By the use of several springs it was possible to increase the force with which the entire bone was kept under constant bending tension. The result of these tests was surprising: Not the expected angulation occurred, but the bone reacted against this force by increasing its resistance with a new enveloping callus and remained absolutely straight (see Illustration 27).

In some cases the bone became so much stronger, that its weight was doubled. Considering the fact that the mechanical stability of a tube under otherwise identical circumstances depends on its exterior diameter (distance of the circumference from the mechanical axis) this would mean quite a considerable increase of the mechanical stability. (See Illustration 28).

Illustration 27.

Marked formation of callus in the femur of a dog after the percutaneous insertion of a strong leaf spring made of stainless steel into the marrow cavity.

Illustration 28.

Right femur of a dog after the insertion of a spring into the marrow cavity which resulted in the doubling of the weight. Normal femur on the left.

This however, is true only in a restricted sense because the newly formed bone is considerably softer in the beginning and the original compacta is reduced partly. This new bone is so soft that it can be carved with a knife, making it very suitable for chip transplantation, particularly as it is an extremely active growing tissue.

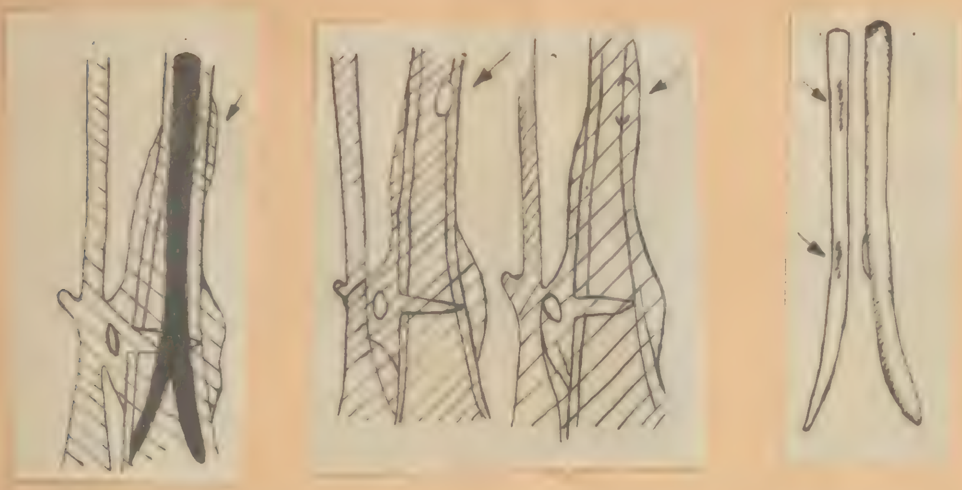
The above roentgenograms reveal that the callus grows radially. This makes the surface of the thickened bone feel rough to touch. If the stimulus is faint, we see only pictures like a "periosteal aggregation" with a marked space between the corticalis and the callus. In case of medium strain on the bone we observe quite regular thickenings, whose development from such aggregations is evident. After a lapse of some weeks the roentgenograms show an increasing dissolution of the border between the corticalis and the callus. The corticalis then in parts becomes poorer in calcium sometimes showing erratically defined, larger, sometimes striated rarefactions.

Later the marrow cavity itself appears veiled, and the border between the two areas becomes distinct. This veiling cannot be ascribed only to the periosteal callus above it, but it is a symptom of a very strong endosteal formation of callus which becomes noticeable by the fact that around the nail a very fine margin develops, about 1 millimeter in width, because the endosteal callus does not grow so far as to touch the nail.

In one single case in literature it was possible to observe a rarefaction of the corticalis in man after a nailing operation. The author owes this observation to EHRLICH (Hindenburg) who had noticed it in an otherwise good callus as a side-effect during one of his femur nailings.

So far, similar observations have not been published. The author himself has observed such a center in the corticalis in only one single case. It was a simple transverse tibia fracture in the lower third caused by the explosion of a bomb, The patient (M.Sch.) was 24 years old and seven days after the accident the marrow nail operation was performed using a wedge-spread nail. Due to the fact that a nail of the required length was not available a much longer nail was provisionally shortened at the head by a locksmith. During this process the plating of the nail was slightly scratched. The operation was successfully finished within a few minutes. In the beginning the healing process was absolutely normal. After a lapse of seven days the patient was able to get up and walk without difficulties. Three months after the nailing however, the patient suffered continuous pains at the frontal plane of the tibia about a hand's breadth above the fracture site which decreased when lying down. At the above described spot we observed a fairly circular thickening of about half a centimeter of the periosteum which felt doughy. In the center of this thickened area a fluctuation was noticeable. Considerable tenderness was observed and the whole picture seemed to indicate a subcutaneous abscess. The skin above that spot however was not flushed and the values of the leukocytes and the blood count were normal.

The X-ray revealed an oval shaped rarefaction of the corticalis the size of two peas which is not in direct contact with the nail (see Illustration 29.)



a b c

Illustration 29.

Oval rarefaction of the bone in the corticalis of the tibia after the marrow nailing.
a) X-ray taken 3 months p.op.
b) after the extraction of the nail 4 months later. The location of the rarefaction corresponds exactly to a rust spot.on the nail.
c) Picture of the extracted nail showing location of scratches in the plating and the exposure of the underlying metal.

The formation of callus was excellent and a reaction of the periosteum up to the rarefaction was apparent. A particularly strong reaction of the periosteum above the center of rarefaction however can definitely not be observed. Such a reaction would have to be expected, if MAATZ's concept of the significance of the bone necrosis for the development of a periosteal reaction were correct.

The nail shows a slight area of resorption. After confinement to bed for 14 days the patient did not complain about pains anymore, and the fluctuation had disappeared. The doughy swelling remained unaltered and a slight tenderness persisted. Four months after the medullary nailing the marrow nail was extracted and we observed a reddish-brown rust spot the size of a bean which, as to its location, corresponded to the rarefaction zone in the X-ray (see Illustration 29). It was only a rusting of the surface which did not penetrate. On the medial preface of the lateral nail there was also a superficial layer of rust. 14 days after the extraction of the nail the clinical symptoms subsided and the patient did not complain about pains any more.

An X-ray taken 4 weeks later proved a considerable regress of the process.

As to the temporal occurrence and to their appearance the pictures of the leaf spring experiments are absolutely equal to the thickening of the ulna of dogs which had been observed during the above mentioned experiments opposite to the resection site of the radius (see Illustration 13), so that there is no doubt that it is the same process in both cases. In both cases there is the same cause, a sudden mechanical over-strain.

The histological pictures also are absolutely identical.

During the leaf spring experiments the following most interesting histological findings are observed: There is an enormous apposition of bone. The border of the exterior layer of the old bone compacta is quite noticeable. While the old compacta has a thickness of 2.1 mm, the thickness of the superposed bone is 16 mm. It shows all signs of a rapid and impetuous growth. Contrary to the old bone the newly grown bone is of desmogenic nature. It shows a very conspicuous regular structure with a radial arrangement of the bone trabeculae which converge to the center. The periosteum is thickened and part of it reaches into the interior of the bone in the shape of a cone and in accordance with the radial arrangement of the trabeculae. The regenerated bone is formed by the periosteum which can be incontestably recognized by the fact that the youngest parts of the bone are located at the exterior circumference and that from the periphery to the central parts the bone shows an increase in age. The border between the old corticalis and the young tissue is distinctly visible. No proliferation of the old bone can be observed.

Two zones are clearly visible in the newly formed callus, which can be seen in the illustration. Both zones show an extremely precipitate growth. In the external layer the marrow sinuses are very narrow and they depend on the vessels of the periosteum. The older internal zone shows considerably larger marrow sinuses. Here the arrangement of the bone arises according to HAVER's system. In the border zone osteogens are observed. Here the secondary transformation of the vessels takes place. The marrow sinuses are filled with fresh marrow and coated with high palisade like upright osteoblasts. In the external layer no process of reduction can be observed. At the same time we do not observe any osteoblastic resorption of the bone but everywhere a precipitate formation of new bone. The broad marrow sinuses show, in some case, considerable distended tightly filled lacunar blood vessels in which the blood is circulating. The high osteoblast margins of the marrow sinuses enclose the freshly built bone substance which however does not or not entirely show the structure of an osteogen. The structure is completely regular and no irregular lines - as for instance in PAGET's disease- are observed. The whole marrow sinus displays a marked radiating system which is due to the course of the vessels. In this way it differs from the histological picture of the callus observed in fractures. The exterior main lamellae are in some cases considerably enlarged. Their inner layers are partly open and extend to fresh marrow

sinuses. The old bone marrow does not show any particular alterations. Neither here nor elsewhere in the bone are necroses, degenerating processes, or other symptoms of a damaging of the tissue observed. Only in the immediate vicinity of the nail is the tissue infiltrated with iron. A similar development takes its origin from the internal periosteum and this causes the marrow cavity to be filled with bone trabeculae (see Illustration 30).

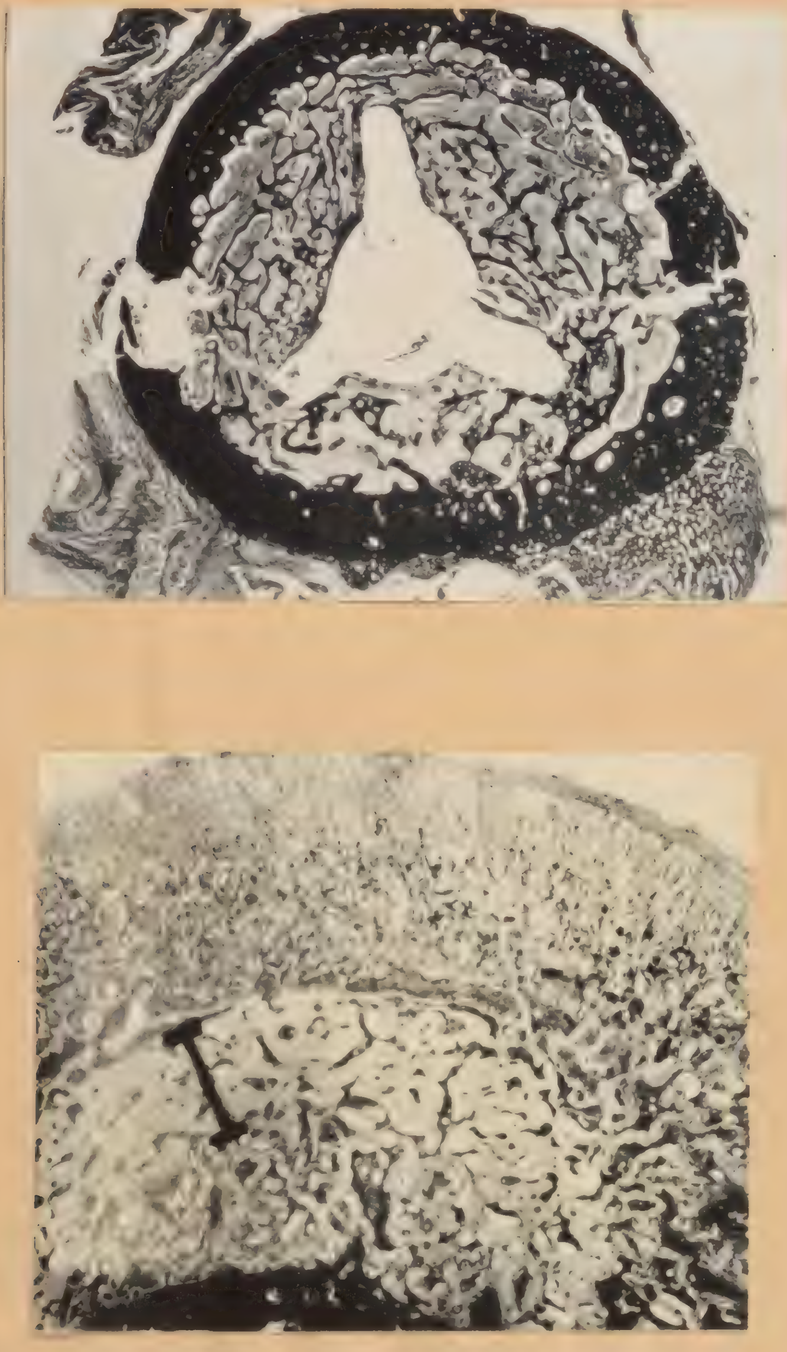


Illustration 30.

Cross section of the thigh-bone of a dog after the irritation of the marrow.
I = thickness of the original corticalis.

The histological pictures of the thickening of the ulna caused by the resection of the radius are strikingly similar to those produced by the marrow leaf springs. Both GREIFENSTEIN and RIX prepared exact histological pictures in which attention is attracted by the regular structure of the cross section. The specific osteogenic layer of the periosteum proliferates. The inactive periosteum which is poor in cells forms a broad germinating layer or germinating internal layer (Keimbinnenschicht) of osteoblasts under lively mitotic fission. The osteoblasts produce an osteoid substance which contains no calcium and in which they are enclosed so that after the onset of the process of calcification they are included in the regenerated bone as bone corpuscles. This periosteal bone is superposed immediately upon the old corticalis. It grows radially, encloses the vessels of the periosteum which in this way are included in the newly formed marrow sinuses, the walls of which are coated with epithelium like monostratal margins of cubic osteoblasts. But also the formation of endosteal callus is considerable and it corresponds to our observations made in the above mentioned tests.

Concerning the X-ray findings, there is also perfect agreement. In the X-rays the development of endosteal callus can also be observed. The blurring of the delimitation of the corticalis and the development of spotted and striated rarefactions are in an absolute agreement.

The callus formed after marrow nailing very distant from the fracture site is absolutely identical in appearance with the callus observed in the above mentioned experiments. Sometimes they are superpositions with a distinct 1-2 mm broad margin containing no calcium between the callus and the corticalis. In most of the cases, thick masses of callus are directly superposed upon the bone. This can by no means be compared with the formations of callus developing in the marrow cavity particularly at the nail tip.

According to the above described experiments there is no doubt that the periosteal superpositions at the described spots result from the mechanical irritation of the nail. The marrow nail has the shape of a V, two sides of which somewhat approach each other elastically through rigorously knocking the nail into the marrow cavity. This constant pressure of the two legs of the nail causes the mechanical irritation.

Each of the above described leaf springs was individually forged of V2A-steel, or of chromium plated steel springs. The "elastic force" of the V2A-steel was only slight. As was shown by numerous preliminary tests, however, this material did not display any recognizeable chemical effects in the marrow cavity, so that this can be excluded. The steel springs plated with chromium were considerably stronger. With these however, there was the danger of injuring the chromium plating when knocking them in so that considerable chemical effects had to be taken into account. As a matter of fact it was revealed that these chemical effects release the same irritation. In the above mentioned experiments a thin wire made of iron or a piece of a nickel plated bone saw blade was sufficient to stimulate the formation of callus (see Illustration 31).

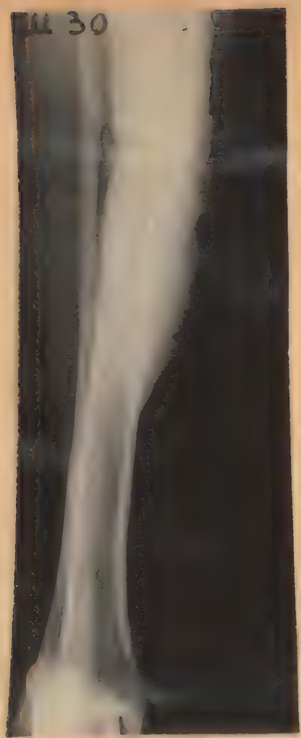


Illustration 31.

Proliferation of callus caused by chemical irritation of the marrow cavity by means of a thin wire. Eight weeks after the insertion into the tibia.

It is striking that at those spots at which the wires are nearest to the corticalis the strongest formations of callus are observed. In this connection best results are obtained by using zig-zag-wires. We have to deal with a chemical effect which is the stronger the less valuable the metal is in the potential series. The effect is strongest by using two different metals as for instance iron and nickel. Valuable metals as for instance pure chromium or copper, do not produce such changes. Copper causes even a resorption margin at the spot of contact with the spongiosa of the tibia head which probably is due to the poisonous effects of the copper ions. Consequently effects of the above described kind are caused by the presence of metallic ions and not by the shifting of the hydrogen ion concentration. All this may be well demonstrated by inserting foreign bodies into the marrow cavity which with the same distance from the endosteum deliver more metal salts to one side. After the insertion of a saw-blade for instance we see much more callus at the side of the saw teeth (see Illustration 32).

It seems unnecessary to deal with the question of whether or not the above described alterations have to be considered as callus. According to the temporal course of these changes, according to the X-rays and the histological pictures there cannot be any doubt about the fact that we have to deal with the same changes which are observed after a bone fracture.

Also W. MUELLER describes the above mentioned thickenings of the ulna as "callus without fracture".

Formations of callus without fracture are most frequently observed after subperiosteal hematomas which are particularly observed on the skull of children and in the tibia. This callus, however, is limited to the area of the hematoma and therefore no metastatic effect is observed.

According to the above irritation experiments some of the periosteal appositions and similar changes which for instance occur in the marrow cavity (as for instance with tumors) were to be considered as due to a similar chemical or mechanical irritation. In those cases the entire process is enacted beginning with the precipitate proliferation of callus and ending with the deposition of calcium. It is quite possible to release this process a second time. The author

was in a position to prove in a 14 year old patient that processes of this kind take place also from the clinical point of view. For half a year the patient had complained about indefinite pains in the distal end of the right arm above the elbow with moderate painfulness of the bone at that spot. An X-ray revealed that we had to deal with periosteal appositions which were piled up in several layers similar to the skins of an onion. (see Illustration 33).

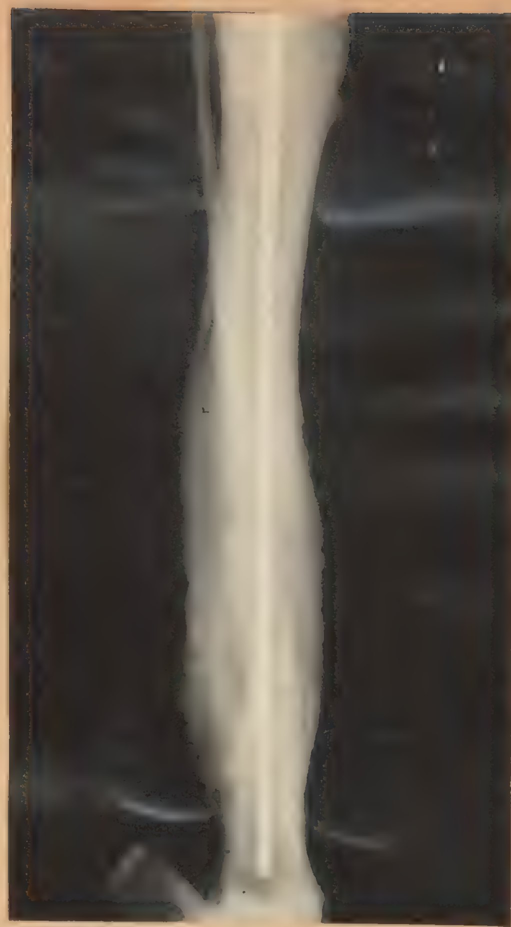


Illustration 32.
Tibia of the dog. Unequal formation of callus due to the insertion of a saw blade into the marrow cavity.

Illustration 33.
Layers of callus deposited like onion skins one upon another due to periodical irritation of the marrow. (personal observation).

There is no doubt about the fact that in this case a medullar irritation had developed which was repeated several times. The cause for these conditions of irritation could not be found despite most thorough clinical examinations. Complete healing was obtained without any particular treatment.

The elastic marrow nail or more easily the "irritating wire" are the means to produce enormous quantities of callus which cannot be obtained by any other way. Through such an irritation the bone is so to speak animated and enormous proliferation of cells is stimulated. This method seems to be simple and without any harmful effect because as in marrow nailings a metal wire is inserted percutaneously into the marrow cavity. Thus the bone itself

must not be exposed to a large extent. This method seems to be absolutely harmless and in no case did a failure result.

MAATZ found in numerous experiments that effects of this kind cannot be obtained in old dogs. REICH however scrutinized a great many clinical cases of marrow nail operations and observed that the formation of stimulated callus decreases markedly with increasing age but that effects of the described kind can still be clearly observed also in persons older than 40 years. This is in conformity with my personal observations.

This method seems to be particularly suitable for all cases of delayed fracture healing and for the treatment of pseudarthrosis. I must point however to the fact that the only thing to be obtained in this way is to release again the mechanism of callus formation.

Due to the fact that the development of a pseudarthrosis principally is not caused by lack of callus but by mechanical conditions an essential part of the therapy in those cases is a simultaneous solid mechanical fixation, i.e. a marrow nailing. In most of the cases a marrow nailing can be obtained only by an operative treatment (see Chapter VI F) because the marrow cavities are closed by bone. In cases of this kind the opening of the bone as a considerable stimulus suffices to release the callus forming mechanism. Consequently the author does not dispose of practical experiences in this connection despite an abundant amount of clinical material at hand. Good clinical experiences were published by STOEHR from the clinic at Marburg who had used a zincplated copper wire for producing a strong irritation. MAATZ has used a zincplated marrow nail for the treatment of pseudarthrosis of the leg and he has observed enormous quantities of callus which extended along the entire length of the nail. The fracture cleft however was not bridged over by callus and he had the impression that the chemical irritation had to be blamed for that.

All these tests give a noteworthy insight in the processes taking place during the formation of callus. The stimulating foreign bodies are seated in the marrow and so it seems that through its irritation the bone is animated to produce callus. This would correspond to BIER's concept who attributes the leading part to the influence of the bone marrow. In this way the marrow would have a formative effect upon the callus similar to the "organizer" of SPEMANN. It is striking, however, to observe the clearly demonstrable fact that the nearer the wire is to the endosteum or to the corticalis, the better is the formation of callus. All this however is easily explained:

Under the supposition that the stimulating effect of round wire extends equally to all sides, the irritating effect in the cavity must decrease in a direct proportion to the square of the distance which can be proved fairly accurately by a series of X-rays. So we have to deal with one of the rare cases in which a biological process can be calculated accurately. This means that in this method of producing callus by stimulation there is something absolutely

regular which can be repeated time and again in the same way. This mathematical proof that the stimulating effect of the wire extends equally to all sides says nothing about the nature of the stimulus and its conduction. There are five possibilities:

1. Electric currents may extend in much the same way.

2. A hormon produced in the marrow cavity could diffuse regularly into the surroundings but this seems to be very improbable. The interpretation of MARTIN who holds that the thickening of the ulna opposite the resection site is a sympathetic reaction and explains it by the influence of an infiltrating hormon would then be correct.

3. A stimulation of the cells originating from the marrow could have the same extension. In the bone substance which does not contain any nerves the bone cells with their prolongations would take over the conduction of the irritation. According to PETERSEN these cells represent the only conduction system of the bone for stimuli.

4. A chemical irritation originating from the wire (such as a metal salt) might diffuse from the wire to all sides and cause and stimulate the periosteum to produce callus.

5. The bone substance itself is stimulated either by the pressure of the spring seated in the marrow cavity or by the chemical effect of the metal salts and forms either callus itself or causes the periosteum to do that.

Theory 1 can easily be excluded by giving the electric currents a particular direction which is most easily achieved by bending the wire projecting from the bone in the downward direction and inserting it into the tissue so that it runs along the bone at its exterior. In no case was it possible to prove such an effect of the bent wire. After the first nailing operations it was possible to prove that a hormon develops in the marrow cavity. In many cases we observed a formation of bone substance on the heads of the nails projecting from the bone, the socalled "little hat". The appearance of those "hats" may be explained in this way that some drops of fat escaping from the marrow cavity run along the slot of the nail and cause a formation of bone as soon as they touch the connective tissue. Histological inspection reveals that those little "hats" consist of bone tissue which is interspersed with thick connective tissue tracts. There is in question either connective tissue or cartilaginous preformed callus (see Illustration 34).

According to BOEHLER this bone sometimes has the shape of a ring. The author observed such a bony ring in one case only.

Illustration 34.

Little "bone hat" grown on a marrow nail due to the stimulation of the connective tissue caused by escaped medullar substance (personal observation).

BOEHLER does not agree with the opinion of this author. He believes that also cellular substance of the marrow plays an important part for the formation of the osseous hats which are displaced during the nailing operation. The author does not doubt that the escaping marrow is of importance in connection with the bone fracture.

Dislocations do not take place during the nailing operation and thus good comparative examinations may be made of the various types of callus which, because of the innumerable types of callus, otherwise would be much more difficult.

So, according to ALSLEV's findings, made in about 100 marrow nailing operations, only four different groups must be distinguished:

1. Cloudy callus,

2. Smaller amount of callus with an ideal reposition and a quick healing process,

3. Formation of callus with preference for one side,

4. Extensive reaction of the periosteum.

In case of cloudy callus we see unusually extensive masses of callus which, however, are less marked in the X-ray. This type of callus may sometimes be observed in cases of fractures with numerous small fragments which are not treated with the marrow nail method. In marrow nailed fractures this callus is observed also without the presence of several fragments but only in thigh fractures. According to the observations made by GRIESSMANN and SCHUETTEMEYER this type of callus was observed not even once in marrow nailed leg fractures.

The second type is frequently observed in marrow nailed leg fractures. In 35 out of 43 cases of nailed fresh leg fractures GRIESSMANN and SCHUETTEMEYER observed this special type of callus. In four cases a very extensive reaction extending beyond the fracture site was observed in the sense of the fourth group. This special type represents the chemical-mechanical reaction of the bone to the marrow nail already described in detail. A chemical reaction is more liable to develop with double nails because of the increase of the above mentioned chemical destruction through the effect of friction. A clearly visible mechanically caused reaction is

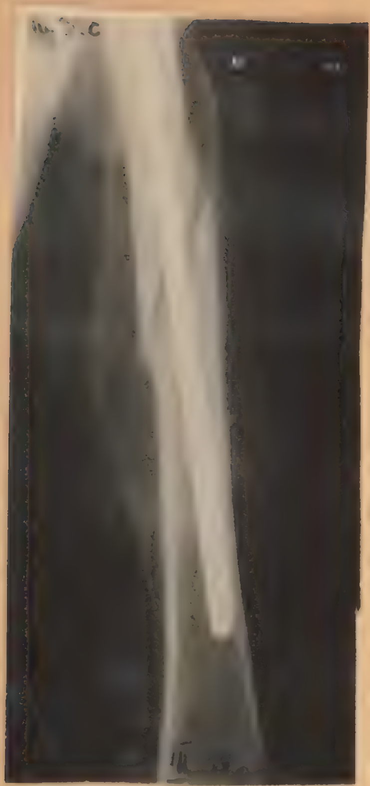
observed only in those cases in which the pressure on the plane is very strong as for instance in that case in which the entire pressure is concentrated at the nail tip.

In two cases the author observed "marrow callus" located in the marrow ca vity. In those two cases the femur had to be shortened so much that the marrow nail remained somewhat loose. The X-ray showed the way of the nail tip (see Illustration 35 f). Sometimes we see also a marked endosteal formation of callus (see Illustration 35d) which frequently is so sharply defined and rich in calcium that they give the impression of sequestra. There are, however no sequestra but living bone which can be established beyond any doubt after further thorough study of this phenomenon.

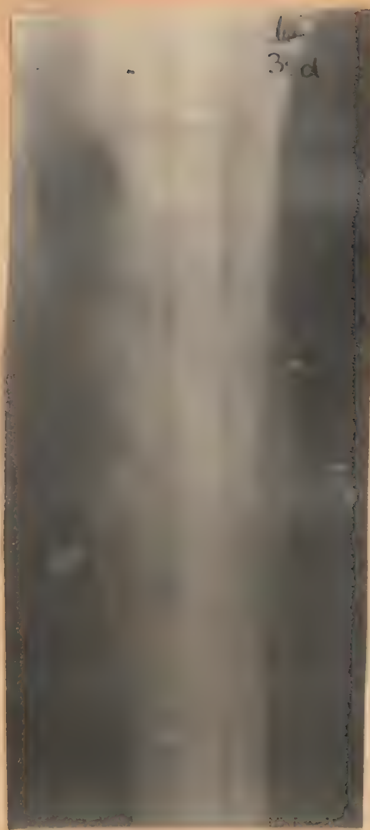
a

b

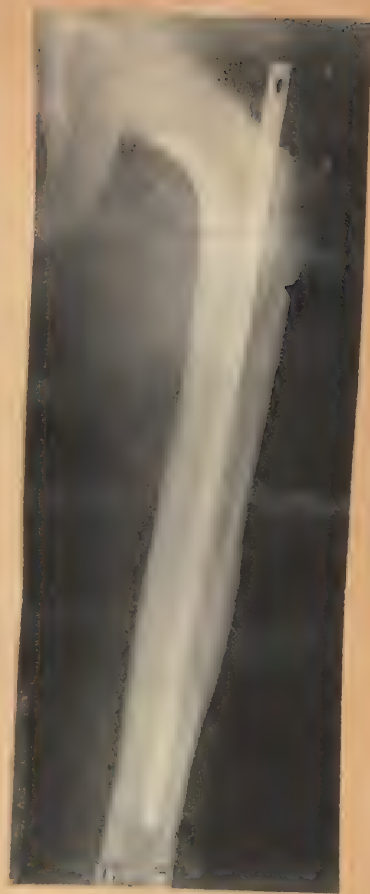
Illustration 35.
The different types of callus in marrow nailed bones according to ASLEV.
a) cloudy callus
b) slight formation of callus after ideal reposition and quick healing.



35c
Formation of callus with preference for one side



35d
Extensive reaction of the periosteum



35e
Endosteal callus with the nail slightly loose

The above mentioned cloudy callus produces the impression that its development is at least partially due to the escape of marrow substance. Logically some marrow substance must escape from the fracture cleft and from the insertion site, i.e. about as much as equals the volume of the marrow nail. The insertion of a 30 centimeter long and 9 millimeter thick femur nail will result in the displacement of about 20 cubic centimeters, which is easy to show by putting such a nail in a measuring glass filled with water.

<ins>In these tests however, the marrow is of no importance at all!</ins> The masses of callus develop also in much the same shape and with the same speed by the stimulating effect of wires, etc. if the bone marrow

35f.
Marrow callus at the marrow nail tip.

and the endosteum is entirely scraped out by means of an excavator which is easily done from the tip of the trochanter.

We must however take into consideration that according to WALTER HOEFER's and SCHRAMM's findings in their demarrowing tests of human bones in cases of pernicious anemia, the marrow regenerates extremely quickly. But even as early as after two weeks, i.e. at a time when the marrow shows only a slight regeneration, an abundant formation of callus is observed in the X-ray. The destruction of the marrow alone, during which process a particularly large amount of hormons should be released, does in no way cause the above mentioned formation of callus. Finally the author made some dog experiments in which the marrow cavities were entirely filled up with wires of V2A steel or glass rods. In the course of one year they caused no change of the bone. After that the non-irritating V2A-steel and the glassrods were replaced by zinc-plated iron wire and immediately an abundant formation of callus ensued. The fact that the marrow itself is not necessary to produce these peculiar effects may be proved in the following very simple way: If the marrow cavity is filled with as many wires of V2A-steel as will fit into it, no callus is formed, because neither a chemical nor a mechanical irritation is called forth. If, however, a thicker peg made of V2A-steel is driven into the bunch of the wires, the marrow cavity will be subjected to pressure as a result of the elasticity of the medullar tube and an ample amount of callus was formed.

The possibility must be borne in mind that a chemical stimulation of the periosteum might be provoked by a wire inserted into the marrow cavity. On the other hand we know from daily experiences that metal splinters located outside the bone at a moderate distance from the periosteum are not able to provoke a noteworthy formation of callus. Callus may be produced by inserting a piece of metal, preferably magnesium, between the bone and the periosteum as was recently demonstrated by NOGARA. The amount of callus produced in this way is by no means as large as that formed in our experiments. Furthermore it is improbable that the mechanical irritation penetrates the bone and acts upon the periosteum. The distension of the periosteum obtained in this way is extremely slight, while on the other hand the presence of such a distension is indispensable for the callus formation. In a certain number of experiments the periosteum in young and old dogs was either stripped or scratched off to the extent of 2-3 cm. and we observed that the above mentioned effects did not develop in this region. It is not likely that the reduction of the blood supply to the involved part of the bone is sufficient to cause a failure of the callus to appear, as the damage done through the scratching off is not great enough.

Besides, the above described histological pictures indicate that this new bone is formed only by the periosteum. After all this there is only one explanation and that is the one mentioned under theory number 5 which says that the bone substance itself is irritated either chemically

or mechanically and that that bone substance causes the periosteum to form the enormous amount of callus.

This is in conformity with old experiments of transplantation made by BARTH which proved that after the separation of the periosteum from the bone a very slight formation of callus is observed, notably in all those cases in which the periosteum no longer touches the bone closely.

The formation of callus in the ulna of the dog which, as was shown, represents the same phenomenon, likewise results from the direct mechanical irritation of the bone substance by increased strain near the resection site. Similar to the findings in experiments made with medullar leaf springs the thickenings observed in this case must be considered as a functional hypertrophy. The above described tests therefore permit a very interesting insight into the mechanism of this process.

There are no objections to applying the above mentioned findings to the process taking place in the bone during the healing of a fracture. Here too, the most important thing is the stimulation of the bone substance and the solitary effect of the trauma seems to be sufficient. Through HAASE's investigations we are informed that in the vicinity of the fracture site there are zones of very strong mechanical stress, the so-called zones of disorganization, in which the irritated bone substance causes the periosteum as well as the endosteum to form callus. Similar strong stimuli of the bone substance may be produced by BECK's drilling, BRANDIS' sawing or KIRSCHNER's splitting method. Without that stimulus upon the bone the periosteum is not in a position to form any noteworthy quantities of callus. All this is in conformity with the experiments of periosteal transplantation. Periosteum transplanted without bone substance cannot form any bone. To the most various chemical, mechanical or thermal etc. stimuli the bone responds with one single reaction only, namely with the process of callus formation.

The further fate of the callus is determined by the mechanical conditions at the fracture site, which were described in detail in the foregoing chapter.

The results obtained in the above described experiments seem to be very suitable to clear the difference of opinion between BIER and LEXER on the formation of callus. They agree with the view of numerous authors who attribute the greater significance to the bone substance.

They are in conformity with O. MAIER's findings who, by inserting a bolt made of magnesium into the fracture cleft, observed an increased formation of callus.

For the marrow nailing all these experiments are of utmost importance. Therefore they had to be put in the foreground in this publication. On the one hand they show that even in those cases in which the marrow cavity had been filled up with foreign bodies which were left there for years, a damaging effect upon the bone has not been observed, and that an abundant callus was formed. Last of all it was observed in the dog experiments of the author in

which artificial fractures were nailed, either by inserting thin leaf-spring nails or massive round nails which entirely filled the marrow cavity. As to the formation of callus a marked difference could not be observed in either experimental series. It was proved how important the part of the periosteum is in connection with the formation of callus, the latter being not only not hampered but actually called forth by the nail even when there is no fracture. Through the selection of the material of the nail the surgeon is even in a position to provoke the formation of normal or excessive callus. The marrow nail cannot injure the periosteum because it does not touch it. If the marrow nail is used employing this idea, an entirely new operative technique may be developed which preserves the periosteum to the utmost extent. Its contact with the bone and if possible, also with the musculature and the other soft parts is maintained so that the hitherto used principle of subperiosteal operation, as suggested by LANGENBECK, is no longer required. It is f.i. quite inapplicable when using wire loops, LANE's plates, etc. which will be referred to in detail in chapter VI A b.

MAATZ regards as the most significant result of the callus proliferations observed in the experiments the occurrence of the circumscribed bone necroses to be recognized in the histological pictures. In any part of the body decayed tissue doubtlessly has a stimulating effect which results in a marked proliferation of tissue of the same kind, as referred to by BIER in his publication on the necro-hormons. Necrosis of that kind, however, is not necessarily required for the explanation of the development of such symptoms. Probably living bone also shows similar effects. Finally this problem is of minor importance. But clear evidence was provided by the experiments that the substance causing the ossification of the callus neither originates in the marrow nor in the periosteum but in the bone itself.

This agrees with LEVANDER's experiments confirmed by ANNERTSEN. Both of them succeeded in extracting a substance from the bone by means of alcohol, ether or benzol, which is fat soluble and specific for the species. Its injection into the musculature provokes the formation of bone. It is thermostable up to 78°C. Similar ossifications were obtained by HENSCHEN, who injected bone autolysates. Furthermore this is in conformity with the experience that bone transplanted without periosteum (see Chapter V 1) also causes the formation of bone, while the injection of the dissolved calcium salts of the bone show no such effects.

The great significance of the periosteum is implied in the fact that the blood vessels of the bone take its origin from it. In itself it has not the capacity to form bone. In all tests in which only the periosteum of adult animals was incontestably transplanted no formation of bone was obtained. The periosteum of the bone invariably disappears and after several days it is replaced by new connective tissue from the adjoining parts. In this way a quicker connection with the surroundings is obtained. This may explain its superiority over the grafts not covered by periosteum. With the CARREL-culture medium periosteum

also does not form any bone, but only connective tissue.

The above described histological pictures show clearly that the formation of the new bone is adjusted according to the rapidly proliferating vasoformative elements of the periosteal vessels. According to LAUCHE the direction and the arrangement of the vasoformative elements determines the course of the future bone trabeculae. These vasoformative elements produce a mesenchymal germ-tissue which is by no means specific and which only under the influence of the agent produced by the bone substance is differentiated into bone tissue.

The vessels are particularly sensitive to X-rays and the failure of callus to develop after irritation with X-ray is in accordance with this fact.

It is a matter of course that also the vessels in the immediate environment of the fracture form vasoformative elements of that kind which likewise produce such a germinative tissue.

Thus we observe that few days after a fresh fracture the partly liquid, partly coagulated fracture hematoma is rapidly filled with fibrous germinative tissue, which in this phase looks like a simple fresh wound.

The proliferation of this mesenchymal tissue is caused by the acidification resulting from the inflammation due to mechanical factors.

After every severe trauma and particularly after a fracture we see a local inflammation the so-called "mechanical" inflammation with all its characteristic symptoms. The initial nature of the inflammation is the excessively increased metabolism, and, as to the physico-chemical background a shifting of the ion-equilibrium to the acid side stands to the fore as well as an increase of the K-ions. This shifting is the result of the failure of the local regulatory processes in front of the increased metabolism. The alteration of the ion-equilibrium may even cause such a condition that the cells are deprived of their vital necessities. We know that every cell is fit to live only within strictly limited physico-chemical constants, the so-called eucolloidal equilibrium (according to H. SCHADE). Due to the necrobiosis of the cells strongly active substances are formed as for instance Leuzin and Tyrosin, free and volatile fatty acids. In case of a fracture this necrobiosis of the cells partly is primarily initiated by the mechanical destruction of the cells. The final products of the increased metabolism are mainly acid products of dissimilation such as organic acids, and CO_2. The K-ions originate from the interior of the cells. Their increase acts in the sense of a vagus-excitation and thus causes a vasodilatation. After the investigations of FLEISCH, ATZLER, LEHMANN and other authors we know that even an extremely small increase of acidity causes a considerable dilatation of the capillaries. Furthermore, according to H. SCHADE's experiments the increase of the pH-values is a very effective stimulus for the multiplication of the connective tissue cells.

This hyperemia probably is promoted by histamine and trebylcholin which in all cases of tissue injuries are liberated causing vaso-dilatation. According to WATSON-JONES and ROBERTS each hyperemia causes a resorption of the bone at the ends of the fragments with a transport of calcium into the surroundings. This process comes to a standstill only if the hyperemia subsides.

During the period of development of the germinative tissue and the resorption of the bone a considerable acidification of the tissue of the fracture site is observable. GOETZE observed in juvenile callus higher pH-values in comparison to normal bone by means of indicators. GREUNE inserted cotton threads impregnated with indicators into the fracture site and observed a shifting to the acid side by 0.2 - 0.4 pH from the third to the fifth day on, lasting into the third week.

ANNERTSEN observed pH-values of 7.5 by means of electrometric and gasometric measurements on the fourth day.

This acidification during the stage of formation of germinative tissue is reversed into a considerable alkalization during the stage of the differentiation of the callus into bone tissue. According to VON KORFF as well as K. SCHMITZ the first phase of callus formation is strongly basophilic, while the second stage is strongly acidophilic. ANNERTSEN also observed a considerable alkalization during the second stage. On the 24th day he observed a pH-value of about 9.0 . At the same time there is an increase of the bicarbonate. This alkalization favors the precipitation of tertiary calcium phosphate which is the principal constituent of the bone salt (bone salt is a multiple apatite which besides calcium phosphate $Ca_3\ (PO4)_2$ also contains calcium carbonate and calcium hydroxide). During the differentiation this salt is precipitated at first as coarse granules in the provisional callus. In the final callus it is converted into a fine crystalline form. During the precipitation the organic substance is of importance, which is clearly shown by the fact that with an increase of the precipitation the nitrogen content is also increased.

Operation on a fracture means the revival of the "mechanical" inflammation. Actually K. SCHMITZ was in a position to prove that during an operation the pH-values increase markedly and constantly in a way similar to the secondary healing of wounds which is in conformity with GOETZE's and BRACHERT's histological investigations. This is of utmost importance to determine the correct time of operation, (which therefore should be performed during the basophilic phase at the beginning of the third week), and also to determine the indication for operation and to gain an opinion on the healing. The intervention itself should be as small and short as possible so that the damages observed during secondary healing do not come too much into the foreground. Detailed descriptions of this problem may be found in chapters VI and VII. Finally any repeated reposition and sudden movement in the fracture site must be considered as a physico-chemical disturbance of the eucolloidal state of its tissue cells.

There is no doubt about the fact that phosphorus is also of considerable importance in connection with the processes taking place in the bone during the healing. According to BOTTERELL and KING the phosphatase content in the callus is increased 6-8 fold. Phosphatase releases a phosphate from the organically bound phosphoric acid and it causes an oversaturation with calcium phosphate of the tissues surrounding the fracture. The detailed discussion of these processes would overstep the limits of this book.

With the reduction of the pH-values to normal and after the definite structure of the callus was formed the automatism of callus formation is run down. A second start of the automatism can be accomplished only by producing the conditions of the first phase, i.e. by acidification and proliferation of the tissue.